Thematic Network for Ultraviolet Measurements

Abstracts for the workshop in Davos, August 27 – 28, 2013

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1 Monte Carlo uncertainty evaluation of UV solar spectral irradiance measurements using array spectroradiometer

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High accuracy UV solar spectral irradiance measurements are challenging because of the rapidly changing atmospheric conditions. Therefore measurements on a short time period <10 s are required. Array spectroradiometers allow to perform such measurements on a time scale that is less than 10 s. However array spectroradiometers measurement data must be corrected for several parameters: stray light, cosine response, linearity, wavelength accuracy, etc. These corrections should be applied also when performing the calibration of the spectroradiometer using a standard lamp.

Thus the measurement model involves a set of equations that describe all the process, from the calibration of the spectroradiometer to the measurement of the UV solar spectral irradiance including the correction steps.

Uncertainty evaluation of the UV solar spectral irradiance measurements must take into account the uncertainty associated to the corrections. Correlations should be considered as these corrections are spectrally dependant. Among these corrections stray light, based on the Line Spread Function (LSF) is complex due to the matrix form describing the process. Because of the huge amount of data to deal with and the correlations between spectral values Monte Carlo technique can be used advantageously to evaluate the uncertainty.

In the framework of the European project ENV03 SOLARUV, task 2.2, we develop a software and the associated guideline that allow the determination of the UV solar spectral irradiance measurement uncertainty. The software uses Matlab for the code as the technique to generate the random number in the Monte Carlo process is validated and is approved in the supplement 1 of the GUM. We present the following items:

- The complete measurement model including the spectroradiometer calibration step and the different corrections that should be applied
- The format of the input quantities and the proposed user interface
- The model to evaluate the contribution of complex uncertainty component such as the stray light correction
- The proposed probability distribution function for each uncertainty components
- The structure of the software
- Example of uncertainty evaluation based on the results of the work performed in the tasks of the work-package WP2.

The software is completed by a guideline that will help the user to determine the uncertainty of the measurements performed. We present the main parts of this guideline.

2 Initial laboratory instrument characterisation and solar simulator measurements of Manchester spectrometers involved in the EMRP project.

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In the field of UV measurements the gold standard for making solar spectral measurements is the double monochromator. These combine sensitivity, low stray light levels and large dynamic range allowing for accurate measurements over the whole range of possible solar irradiance values. The main drawbacks in the use of these instruments is cost, the need for highly trained personnel to operate and time taken to measure a complete spectrum. In comparison the development of array spectrometers had led to the availability of instruments of much lower cost which can take complete spectra in milliseconds. But before these can be fully utilized there are several problems that have to be overcome as they suffer from low quantum efficiency at shorter wavelengths, much higher stray light levels (as they use a single monochromator), and smaller dynamic range.

As part of the EMRP project two array spectrometers (a 2 channel Metcon photodiode array and a 2 channel Ocean Optics CCD array) will be run in Manchester. The Metcon will be run over one year and the Ocean Optics will also be deployed for at least a month in each season. Each array spectrometers will measure both the global and direct solar irradiance. As part of another study a Bentham DTM300 will be used to make both global and direct irradiance measurements and the data from these measurements can be used in quantifying the results from the array instruments.

Before deployment the two array instruments were characterized and calibrated in the laboratory here in Manchester. The main area of work concerned the correction of the stray light as from previous work this was found to make the biggest contribution to error at the shorter UVB wavelengths. As instrumental stray light is dependent on the instrument and the light source (e.g. calibration lamp, sun) the stray light distribution function was measured using a 408 nm laser which can be used to produce a matrix to calculate the stray light for a particular source. Then as part of the checking procedure measurements of a solar simulator were used to optimize the stray light correction method.

3 A modelling approach to determine how much UVB radiation is available across the UK for the cutaneous production of vitamin D

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The UK's current nutritional guidelines assume that from school to retirement, vitamin D requirements are met by skin exposure to UVB in sunlight. However, it is well documented that at latitudes such as the UK, the sunlight in the winter can be insufficient to synthesize appreciable vitamin D levels. We are funded by the UK Department of Health to provide data to inform new national guidance on vitamin D acquisition.

In this study we use a well-established radiative transfer model to map the available UVB across the UK during the last 10 years (2003-2012). A suite of data (aerosol optical properties, surface reflectivity, cloud optical depth and coverage, total ozone column and digital elevation) derived from satellite estimates are used as model inputs to calculate the spectral UV irradiance and the vitamin D dose for different time periods.

The model-derived vitamin D doses are validated against spectral irradiance measurements at Reading (51.44N, 0.94E) and Manchester (53.47N, 2.23E). Results from more than 2500 days at each site reveal that the modeled dose is overestimated by 5% while the overall agreement is satisfactory (R_2>0.9) since the ground-based measurements are not always representative of a typical satellite measurement pixel. On a monthly basis, the overall agreement is significantly improved (bias <2%, R_2=0.99).

The model results will be combined with controlled exposure studies that determined how much vitamin D is synthesized per dose of UVB in adults with different skin types. This enables an estimate of the vitamin D effective exposure available across the UK for different skin types under realistic climatological conditions. Further studies provide for a range of actual exposure patterns within the theoretical availability.

4 Calibration of the QASUME reference spectroradiometer for the terrestrial solar UV irradiance measurements

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Quality assurance of the solar spectral ultraviolet radiation measurements at the European UV monitoring sites and harmonisation of the results are based on a portable reference spectroradiometer, the QASUME, operated by the Physikalisch-Meteorologisches Observatorium Davos (PMOD/WRC). The calibration of the spectroradiometer since the begin of the Q.A.S.U.M.E. project has been traceable via a set of transfer standard lamps to the spectral irradiance scale at the Physikalisch-Technische Bundesanstalt (PTB) realised by a high temperature blackbody. One of the aims of the EMRP-project ENV03 "Traceability for surface spectral solar ultraviolet radiation" was to shorten the traceability chain and to reduce the associated transfer uncertainties. As an alternative to the source-based calibration chain, a direct calibration of the QASUME with the help of wavelength-tuneable lasers against a calibrated trap detector fitted with a calibrated radiometric aperture was considered. Within the framework of this project, the tuneable laser facility at the PTB, TULIP, was upgraded by mode-locked lasers and prepared for the operations throughout the solar UV spectral rage, 280 nm to 400 nm, and beyond. To enable the calibrations at the TULIP facility, a laser monochromator has been built, an active stabilisation for the laser power has been implemented and a novel beam conditioning unit providing a spatially homogeneous and depolarised irradiance field has been developed and will be presented during the talk. The traceability to the primary standard of the radiant power, the cryogenic radiometer of the PTB, is provided by silicon trap detectors built and characterised for this purpose.

The first of the two measurement campaigns planned within the EMRP project and involving the calibration of the QASUME spectroradiometer at the TULIP facility against the trap detectors followed by a direct calibration against the high temperature blackbody was arranged in spring of 2013. The results of the calibrations will be presented in the talk.

5 Application of a dual-channel solid state spectrometer to measure spectral surface radiation and atmospheric constituents: some early results and practical considerations

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Scanning spectroradiometers are the gold standard in terms of accurate traceable radiation measurements whilst the instrument of choice to determine the total ozone column is the Brewer spectrophotometer. Although scanning spectroradiometers are the most accurate, especially at the shortest UV wavelengths, they suffer some disadvantages: high cost, susceptibility to movement, and speed of operation. In contrast solid state spectroradiometers offer reduced cost and more rapid data acquisition but suffer issues with stray light contamination, reduced response at the short wavelengths, and limited dynamic range.

Here we describe the calibration and design of a two-channel solid state instrument covering the UV and visible wavelength ranges, one channel of which measures global irradiance and the other measures the direct solar component by being fitted to a commercially available suntracker. This combination of instruments (a dual channel spectrometer plus suntracker) has been deployed in a monitoring context at a city centre location in Manchester, UK. The dual channel nature and choice of input optics allows determination of spectral direct, diffuse and global components of the incoming radiation to be measured, and additionally, by way of differential optical absorption spectroscopy, estimates of the total ozone column and other atmospheric constituents. Preliminary results are presented and compared against a co-located Brewer spectrometer operating as part of the GAW network. Comparison will also be made against satellite-retrieved total ozone column values. Consideration will be given to aspects such as selection of appropriate absorption functions during the procedure, determining the most appropriate integration time and scheme for unattended operation, as well as practical issues such as maintenance and field calibration procedures and timings.

6 Calculations of street level spectral irradiances using the Google Street View photographic database: Implementation and potential applications on ultraviolet light studies

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Recent trends in atmospheric studies point towards a better understanding of the processes occurring at smaller scales, in order to create more accurate models of the weather and radiation exposure conditions that affect people in everyday life. Particularly, the urban atmosphere at street level is of special interest, both because of its relevance to a large proportion of the human population and the distinctive phenomena that can be observed in it. Many of these distinctive features in the urban micro-scale can be related to the simple concept of Sky View Factor: At any location within a city, the geometry of buildings exerts unique obstructions of the sky view, which in turn may affect not only the energy inputs and outputs at that specific location, but also aspects like human thermal comfort and human exposure to ultraviolet radiation. For large areas, local conditions will sum up and interact with each other, in order to create the complex patterns of urban weather.

However, current methods for describing the urban geometry for atmospheric purposes are not cost-effective. For instance, digital 3D mapping of cities will return wide geographic coverage but at the cost of low resolution and an undetailed representation of urban canyons. On the other hand, “fisheye” photographs of single locations will allow detailed descriptions at the cost of narrow geographic coverage. As an alternative, the Google Street View TM web app possesses a large, free-access database of street photographs, readily available to be used as reference for describing urban geometries. Results would comprise accurate descriptions of single locations, plus widespread coverage of populated geographic regions around the world. The use of digital image processing software (Hugin, ArcGIS, Maxent) allows the semi-automatic reconstruction of a fisheye projection from Google Street View photographs. Irradiances (either total, spectral, or spectrum weighted) can be calculated on the basis of the visibility of the solar disc and the sky view factor affecting the diffuse component of irradiance. Thus, the aforementioned projection combined with solar irradiance calculation algorithms (Rayman, Libradtran) allow the modelling of urban canyon solar irradiances. The special needs for each kind of modelled irradiance will be discussed. Potential applications of these models may range from street photovoltaic generation, energy budgets calculations, and models of human exposure to biologically active radiation.

Keywords: Urban Canyons; Spectral Irradiances; Google Street View; Fisheye Projection.

7 Experiences with miniature CCD- spectrographs for UV-VIS solar and sky radiance measurements

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Three miniature spectrographs have been used to measure atmospheric and solar radiance in the ultraviolet and visible spectral regions, aiming at retrieving total and tropospheric column densities of different atmospheric trace gases with the DOAS technique. The spectrographs have been tested for use in the Phaethon system in order to improve its capabilities in retrieving additional gases, and have been developed: one by Ocean Optics (Maya Pro 2000) and two by Avantes (AvaSpec-ULS2048X16 and AvaSpec-ULS2048LTEC). Among the factors that limit the applicability of the spectrometers in DOAS applications are: the level of the dark signal and its dependence on integration time and operating temperature, the signal to noise ratio in solar and sky measurements, the stability of the spectral resolution with wavelength, both in terms of center wavelength and shape (slit function), deviations from linear response and the stray light rejection efficiency. We compare the performance of the three spectrographs from these tests and we discuss the relative importance of the characteristics of the spectrographs in DOAS measurements.

8 Hybrid detection system for the solar reference UV solar spectrometer QASUME

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In the framework of the EMRP ENV03 project a solid state based detection system SSDS has been developed with the ambitious goal of reducing the total uncertainty of existing photomultiplier-based QASUME facility below 1% in the UV range of interest that spans from 290 nm to 400 nm. For the first prototype of SSDS, 3 state of the art small area Si detectors were chosen as optimal option based on their geometry and noise performance. The front-end electronic is based on low noise and high sensitive switching integrator amplifier.

This detection system was characterized both for its linearity and noise performance. The linearity was measured to be better than 10^{-4} down to few pW level. The noise floor of the detection system has been measured in dark conditions to be comparable with the noise generated by the Si detectors chosen at room temperature and have been found as low as 10 fW/Hz½.

A measurement campaign in DAVOS carried out in October 2012 demonstrated that the QASUME equipped with the first SSDS prototype was able to scan the solar UV spectrum from 310 nm to 420 nm with relative noise level <1% in various sun light conditions. In the wavelength range between 290 nm and 295 nm the number of photons at the output of the QASUME exit slit can be as low as 2000 photons/s which is lower than the fluctuation of the number of thermally generated charge carriers in the SSDS silicon photodiodes at room temperature. To improve the uncertainty in this region of UV solar spectra a new hybrid detection system is under development. The hybrid system is composed by a new prototype of SSDS combined with latest generation photon-counter (PCT) with spectral responsivity optimized for UV radiation. The photon-counter detector covers only the short interval of UV solar spectra from 285 nm to 310 nm. The QASUME's monochromator output radiation impacts both detection systems at the same time. The SSDS provides reference values from 420 nm to 305 nm while the PCT measures the solar spectrum down to 280 nm. It is proposed to use the overlapping spectral region between the two systems to correct for non-linearity and fluctuations of quantum efficiency of the PCT device.

9 Fabry-Perot etalon for characterzing the wavelength scale of UV spectrometers

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Accurate wavelength calibration is a key parameter for solar spectral measurements. Typically, spectroradiometers are calibrated with spectral emission lines. However, for small spectral ranges, where only one or two lines are present, the calibration becomes inaccurate. Furthermore, the accuracy of the calibration may locally vary according to the number of nearby calibration line, their different intensity and the nonlinear relationship between wavelength and recording pixel or grating drive. A possible work around this problem has been presented by Balmer and Heuberger [1] using an Fabry-Perot etalon based on Mica. Unfortunately Mica has a high absorptance in the UV region. In the frame work of the EMRP-project ENV03 "Traceability for surface spectral solar ultraviolet radiation"different Fabry-Perot etalons were realized and characterized with respect to temperature, uniformity and angular dependences. The Fabry-Perot is based on a thin layer of fused silica coated on both sides by semi transparent mirrors. For this purpose a 525 µm thick $SiO2$ (silica) substrate was used as support. A first mirror was created by sputtering a 10 nm thick Al layer on one side of the substrate. At the next step a 3 µm to 9 µm thick fused silica layer was created using a Low Pressure Chemical Vapor Deposition at Low Temperature Oxide (LPCVD-LTO) process. A second Al mirror was deposited with a thickness of 10 nm using sputtering process.

Furthermore the method was compared to classical method and a new type of wavelength ruler based on polarization optics. The results of both approaches are very promising and may allow decreasing the uncertainty of wavelength calibration in UV spectrometers to below the 0.05 nm level.

[1] Perret, E., Balmer, T., & Heuberger, M., Self-consistent algorithm for calibrating spectrometers to picometer accuracy over the entire wavelength range. Appl . Spectrosc. , 2010, Vol 64(10), p 1139-44.

10 Stray light characterization and correction methodologies tested with a modified array spectroradiometer

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Solar UV irradiance measurements with array spectroradiometers can measure an entire solar UV spectrum quasi simultaneously. The instruments, however, suffer from the impact of stray light resulting in significant biases in particular in the wavelength regions with low irradiance levels and large changes in intensity. Stray light can originate from radiation with wavelengths within the spectral range (in-range) measured by the array spectroradiometer or outside (out-range) of the working spectral range of the instrument. A commercially available array spectroradiometer - Avantes AvaSpec-ULS2048x14, with a Hamamatsu back illuminated CCD - covering the wavelength ranges between 280 nm to 440 nm was characterized with a tuneable laser facility PLACOS at PTB in Braunschweig to measure the line spread functions for in-range and out-range radiation. Based on this characterization, a matrix-based stray light correction-method was applied to correct the in-band and out-band solar UV radiation and the results were compared with those obtained using a double monochromator scanning spectroradiometer.

First tests showed that out of range radiation, which is still within the responsivity range of the silicon detector, significantly contributes to the stray light at wavelength shorter than 320 nm. Therefore, a solar blind filter DUG11X was inserted after the entrance slit of the instrument, which allows passing radiation between 290 nm – 380 nm to the detector, while blocking all radiation from longer wavelengths. With this modification only in-range stray light correction is needed. The modified instrument was again characterized by the PLACOS facility to determine the new line spread functions at different in-range wavelengths. The array spectroradiometer and the in-range stray light correction were then tested with the solar UV measurements at different solar zenith angles under clear sky and cloudy conditions. The obtained spectra were converted to a uniform wavelength grid and a constant nominal bandwidth using a software tool and a high resolution reference extraterrestrial spectrum, both developed within the framework of the EMRP ENV03 project for this purpose. The comparison with solar UV spectra measured with the double monochromator spectroradiometer reveals that an agreement between the two instruments of better than 5% for wavelength greater than 305 nm can be obtained with this stray light correction method.

11 Characterisation of the IMU array spectroradiometer

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Since several years an array spectroradiometer (Ocean Optics USB4000) is in operation at the Innsbruck Medical University (IMU), Division for Biomedical Physics, in order to measure solar radiation in the UV and visible wavelength range with 3648 pixels between 200 nm and 900 nm. Besides the characterisation at the beginning of the operation, a new option for characterisation on highest level of quality came up through the participation at the EMRP-project ENV03 "Traceability for surface spectral solar ultraviolet radiation". In this framework the line spread functions (LSFs) were determined with high accuracy for the whole wavelength range by using tuneable laser systems at the Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig and at the Eidgenössisches Institut für Metrologie (METAS) in Bern. From these measurements the stray light correction matrix was derived. A significant role plays also the "out-of-range stray light", which originates from wavelengths, which enter the spectroradiometer, but which are out of range of the detecting array. With our instrument this covers the range from 900 nm to 1100 nm. The application of stray light correction algorithms to measurements of reference lamps as well as to solar radiation is presented. Furthermore, the band-pass (full width at half maximum) is determined in dependence on wavelength. Different methods for describing the band pass function, which is significantly unsymmetrical especially at the higher wavelengths, are discussed.

The wavelength calibration was carried out in the traditional way by using spectral lines of different lamps (Hg, Ne). A newly developed method using a Fabry-Perrot element is tested for the first time in order to give high spectral resolution of the wavelength calibration.

Furthermore, the nonlinearity of the instrument was determined in the laboratory in Innsbruck with the "two lamp method" for both aspects, nonlinearity of the detector and nonlinearity of the data acquisition system.

12 Qasume Site Audits

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The transportable reference spectroradiometer "QASUME" has been used for quality assurance of spectral UV measurements performed by European UV monitoring sites with stationary UV spectroradiometers since 2002. Through these site audits the measured data at these sites could be quality assured to meet the needs of the scientific community. Furthermore, the audits aimed at improving the data quality at European UV monitoring sites and at harmonizing the results from different stations and monitoring programs in order to ensure representative and consistent UV radiation data on a European scale. As of 1st January 2013, the PMOD/WRC has been recognized as a World Calibration Center (WCC) for UV radiation by the World Meteorological Organization, Global Atmosphere Watch Programme (WCC-UV).

The core of Qasume is a commercial DM150 double monochromator (Bentham) mounted in a temperature stabilized box. The fiber coupled and temperature controlled input optic was optimized for a low cosine error. Within the framework of the EMRP ENV03 project a second Qasume II system is currently under development.

Since 2002 audits at 54 different sites were performed in 16 European countries. During the measurement campaigns UV irradiance data from 60 instruments were traced back to the European irradiance reference. In total 138 site audits (including multiple visits) were performed.

A Qasume site audit lasts for at least two full days from sunrise to sunset, under non raining conditions. The schedule is to measure solar irradiance from sunrise to sunset in intervals of 30 min or less - synchronized wavelength by wavelength with the local UV spectroradiometer. These measurements reveal many properties of the stationary instrument: The deviation of its irradiance scale relative to the QASUME reference, potential errors of the entrance optics, temperature effects of the system and the quality of the wavelength calibration.

13 A wavelength ruler for the solar UV wavelength range

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For the measurement of solar UV radiation that reaches the earth, there is a need for improved accuracy of the wavelength scale. Due to absorption by ozone for wavelengths below 330 nm, a large dynamic range is required for measuring spectral irradiance throughout the solar UV wavelength range (280-400 nm). This also puts stringent requirements on the accuracy of the wavelength scale, since a small difference in wavelength implies a large difference in spectral irradiance, when measuring close to the edge of the ozone absorption. For this reason a wavelength accuracy of 50 pm is needed.

In order to compare and to calibrate the wavelength scale of UV spectroradiometers, we have developed a wavelength ruler that is based on a one-stage Lyot filter. The filter consists of two linear polarizers with transmission axes aligned to each other. Between the polarizers a birefringent quartz plate is inserted with its crystal axes (slow and fast axis) aligned at 45° with respect to the polarization axis. The quartz plate has a nominal thickness of 0.7 mm and is thermally stabilized within 0.1°C. Due to the birefringence of the material, a polarization rotation is induced. The polarization state after the quartz plate depends on thickness, refractive index and wavelength of the light. As a result, the amount of light that is transmitted by the second polarizer is wavelength dependent (see Fig.1). We have applied the wavelength ruler for comparison of several spectrometers in a measurement campaign in Davos in January 2013. For this comparison a plasma-based light source has been used for delivering a nearly collimated, broad-band beam through the wavelength ruler. The wavelength-modulated output has been measured with three different spectroradiometers. Furthermore two fixed laser wavelengths have been measured as additional references. From the measurement data the thickness of the quartz plate has been derived through a Levenberg-Marquardt inverse algorithm. The wavelength deviation of the spectroradiometers compared to the wavelength ruler has been plotted in Fig.2.

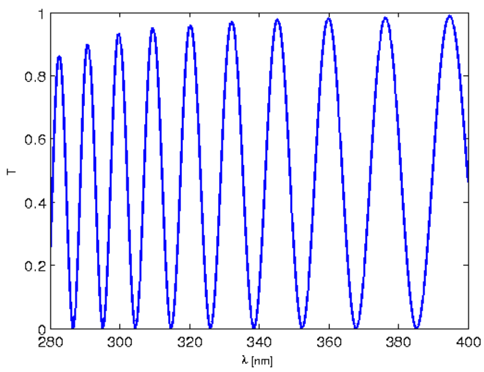

Fig. 1. Simulation of the transmission of the wavelength ruler as a function of wavelength. The lower transmission at short wavelengths is caused by absorption of the polarizers

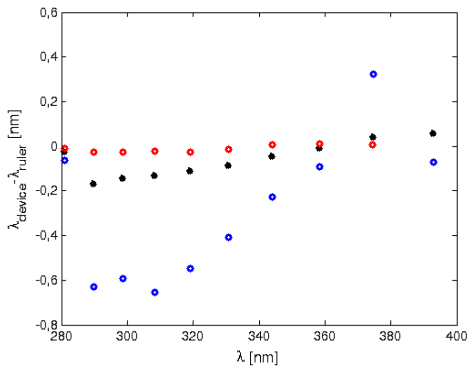

Fig. 2. Deviation of 3 different UV spectroradiometers with respect to the wavelength ruler.

14 Characterization of light-emitting diodes in the solar UV spectral range

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Currently, the stability of the responsivity of UV spectroradiometers is monitored by using tungsten-halogen lamps in most cases. As these monitoring sources are used during calibration in a laboratory and also outside the lab environment at different measurement sites, it is not only required that they are stable, but also compact, portable, and robust. Part of the work in the European Metrology Research Programme (EMRP) project ENV03 is the investigation of an alternative to tungsten-halogen lamp-based monitoring sources. These newly developed monitoring sources use commercially available light-emitting diodes (LEDs) in the solar UV spectral range (280 nm – 400 nm). Further requirements for the new monitoring sources are aging rates (drift in irradiance) of 0.05% per hour or less, and a minimum spectral irradiance of 1 (mW/m²)/nm (wavelengths below 330nm) and 5 (mW/m²)/nm (wavelengths above 330nm), respectively.

For this purpose, and shown in this paper, twelve different types of UV-LEDs with peak wavelengths from 285 nm to 437 nm were characterized in a fully automated setup where the current, voltage, temperature, and irradiance of each LED was recorded. The LEDs have been operated for 120 to almost 600 hours in order to pre-age the devices and determine their stability (drift in irradiance). The best-performing devices have been selected for their use in a prototype of the newly developed UV-LED based monitoring source. First results obtained with the assembled prototype are very promising and will be shown in the paper.

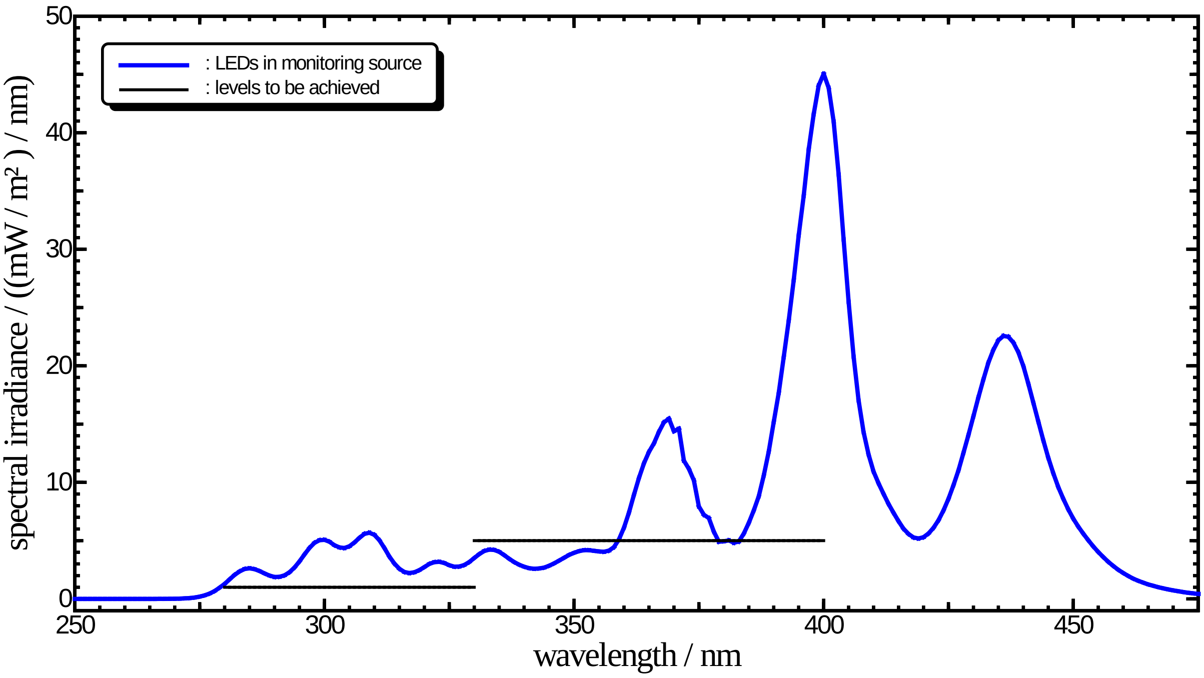

Figure 1. Spectral irradiance obtained with the UV-LED source prototype.

15 Characterization of broadband UV radiometers in the Arpa Piedmont Optical Laboratory and intercomparison with the World Calibration Center for UV (WCC-UV)

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UV monitoring networks for the measurement of UV index have been developed during the last years in Italy. These monitoring networks are based on stations allowing continuous measurements through the use of broadband radiometers with spectral response matching the erythemal action spectrum.

Since the radiometer spectral response differs from the erythemal action spectrum, it was necessary to set a specific calibration procedure for solar radiometers, in order to obtain accurate and reproducible UV index data. This procedure consists of two steps. Firstly the radiometers are characterized in laboratory, measuring their spectral and angular responses. Secondly the radiometers are exposed to solar radiation and the absolute calibration factor is calculated by the comparison to a reference spectroradiometer. The aim of this work is to show the results obtained by the Arpa Piedmont Laboratory from the characterization of two mainly used radiometer types. Moreover the comparison of these results with those obtained by the World Calibration Center for UV is shown.

The results point out the operative difficulties associated to the laboratory characterization, with particular reference to the spectral response in the region where the radiometers are less sensitive. These difficulties make necessary a fine tuning of the instrumental chain, in order to obtain a good radiometer characterization and consequently accurate and reproducible measurements of UV index.

16 Efficiency of vitamin D production by the solar UV radiation, solar simulated radiation or sunbed radiation and influencing parameters

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In the mid latitudes in winter time the vitamin-D-effective irradiances of the sun drops down to a level resulting in a 25OHD-deficiency < 20 ng/ml in greater fractions of the population. Pronounced higher solar UV-exposures in summer could attenuate the winter deficiency, but this would increase the skin cancer risk.

This is the background of the BfS-research project*) "UV-dependent Vitamin D3 synthesis – balancing of the UV exposure time and production of the optimal need of vitamin D3 in men".

In the multiple studies the efficiency of UV-radiation on the increase of the vitamin-D-status (25OHD, 1,25OHD) was investigated for solar radiation vs. solar simulated radiation vs. sunbed radiation. Six serial exposures were applied at first to face and hands – the typical irradiated skin areas in everyday life. A washing out phase was followed by six serial UV-exposures to the whole body. Beside irradiated skin area and variation of the applied UV-dose in steps of 10 %, 30 % or 70 % of volunteers individual MED the included parameters were phototype, age, sex, degree of pigmentation. Further investigated parameters were epidermal skin thickness of the different body sides and the BMI.

The 7-DHC-concentration was controlled in unexposed skin and UV-exposed skin (0.35 SED; 1.05 SED; 2.5 SED) with respect to the above mentioned parameters.

In everyday life individual behaviour on one hand and global impact such as weather condition in the different years on the other hand contribute to the variations of the vitamin-D-status in the subjects and in the population. This was underlined by the resulting vitamin-D-status in 40 volunteers of a two years study and the additional data by a personal UV-monitoring including meteorological data and global radiation measurements.

The results of this study will be the basic for well-balanced recommendations to the different fractions of the population on optimal UV-exposures, realising health protection aspect against detrimental UV-effects.

*) German Federal Office for Radiation Protection (BfS): support-N° StSch 4538

17 Characterization and Calibration of a Fourier Transform Spectroradiometer for Solar UV Irradiance Measurements

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It is the goal of the European Metrology Research Project ENV03 "Traceability for surface spectral solar ultraviolet radiation" to improve the traceability of spectral solar UV radiation measurements at the Earth's surface by optimizing existing reference instruments and by developing new techniques and devices. In particular, the feasibility of a commercially available Fourier transform spectrometer (FTS) as an alternative reference spectroradiometer will be examined within this European research project. Considering the demands for solar UV irradiance measurements, the usage of Fourier transform spectroradiometers may improve the dissemination of absolute irradiance scales due to the specific advantages of these instruments [1, 2]:

- Fourier transform spectrometers have a high throughput (Jacquinot or throughput advantage).
- There are no diffraction losses to higher-order spectra as it is the case in grating spectrometers.
- The whole spectrum is measured simultaneously which allows fast measurements (multiplex advantage).
- Fourier transform spectrometers cover broad spectral ranges with high resolution and high wavenumber accuracy.
- 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.
- Instrumental distortions are often calculable and correctable.

Within the research project ENV03, a Bruker FTS VERTEX 80v has been adapted for measurements in the ultraviolet spectral range from 280 nm to 500 nm by adding UV detectors (Si and GaP) and an UV beam splitter. Furthermore, a global entrance optics has been fitted in order to perform solar UV irradiance measurements. This modified FTS is characterized with respect to the suitability for solar UV irradiance measurements with low uncertainties.

The spectral responsivity of the FTS which is mainly determined by the responsivity of the used detector and by the properties of the beam splitter will be determined against the calculable radiation of a black body radiator with known temperature [3, 4, 5]. Further characterization measurements include the wavelength uncertainty and resolution, the stability of the instrument, and the S/N ratio of the instrument with respect to solar UV measurements. The characterization measurements and the absolute calibration of the instrument will be presented.

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18 Autonomous Portable Solar Ultraviolet Spectroradiometer (APSUS) - a new diode array spectrometer system for localised, real-time solar ultraviolet radiation measurement

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Terrestrial solar ultraviolet (UV) radiation has significant implications for human health and increasing levels are a key concern with regards to the impact of climate change. Monitoring solar UV radiation at the earth's surface is therefore of increasing importance. A new diode array spectrometer based system has been developed that monitors UV radiation levels at the earth's surface. It has the ability to feed back this information to the public in real-time. The new instrument at the centre of this system is called the Autonomous Portable Solar Ultraviolet Spectroradiometer (APSUS). This instrument incorporates an Ocean Optics QE65000 spectrometer which is contained within a robust environmental housing. The APSUS system has been designed to gather reliable solar UV spectral data from approximately March to October inclusive (depending on ambient temperature) in the UK. Example solar UV spectra and UV Index values from London and Weymouth in the UK in summer 2012 are presented.

19 Developments of AlN photodiodes for UV Solar Observations

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For next spaceborne solar ultraviolet (UV) radiometers, innovative metal-semiconductor-metal (MSM) photodetectors based on wurtzite aluminum nitride (AlN) are developed and characterized. A set of measurement campaigns and proton irradiation damage tests are carried out to obtain their UV-to-visible characterization and degradation mechanisms. Results on large area prototypes are presented. In the wavelength range of interest, MSM-AlN is reasonably sensitive and stable under brief irradiation with a negligible low dark current. No significant degradation on the detector performance has been observed after exposures to protons with 14.4 MeV energy showing a good radiation tolerance up to 1×1011 proton/cm^2.

Figure 1: Photographs of the AlN MSM photodiodes mounted on ceramic packaging. The MSM area are (from left to right) 4, 3, 2 and 1 mm diameter with 2 µm interdigitated finger width and 5 µm spacing between two electrodes.

20 Laboratory of Optical Radiometry and Dosimetry of the University of São Paulo – Ribeirão Preto Campus

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The laboratory of optical dosimetry is located at the Physics Department of one of the campi of the University of São Paulo, in the northeast of the state of Sao Paulo, in the city of Ribeirão Preto (-21.167177,-47.848099). The research activities conducted in this campus focus mainly on the medical, dentistry, and pharmaceutical areas; this same campus is located in an important area for agriculture including sugarcane and orange production.

The activities in the area of radiometry conducted in our laboratory cover ultraviolet, visible, and infrared radiation measurements, including the characterization of laser systems for medicine and dentistry [1]. We also research sources for photochemistry application and more recently spectral radiometry of solar ultraviolet radiation, aiming at photodynamic therapy of plant-pathogenic fungi [2, 3].

The goal of the laboratory is to expand the activities related to UV spectroradiometry, including daily acquisition of solar emission, to provide the community with the spectral irradiance, total integrated irradiance, and luminosity. These parameters would be useful for the skin cancer epidemiology and dermatology research community; they could also help monitoring how UV light impacts biodiversity and can employed to promote increased productivity in agriculture and better plant pathogenic control. In this sense, the laboratory is equipped with calibrated spectroradiometers and a calibrated halogen-deuterium source that checks the spectroradiometers calibrations.

Targeting optical dosimetry for solar radiation, the laboratory explores the effective irradiance [$W\ mol^{-1}$]; i.e., determination of the power absorbed per molecule when a source with a certain spectral irradiance [$W\ m^{-2}\ nm^{-1}$] interacts with a substrate of known molar absorptivity [$m^2\ mol^{-1}$]. This dosimetry is very important to measure not only the spectral irradiance or the total integrated irradiance, but the effective radiation that will be absorbed by the irradiated substrate.

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21 Sahara dust effect on solar UV radiation components

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A mineral dust plume was observed from solar radiation measurements at the BSRN site Lindenberg (52.2086° N, 14.1213° E) on August 19, 2012 [1]. Optical aerosol measurements using Precision Filter Radiometers show Angstrom coefficients decreasing from around 1.8 in the morning hours to about 0.8 in the afternoon, and turbidity coefficients increasing from about 0.02 to 0.10 during the same time. These changes correspond to increasing aerosol optical depths at 500 nm from about 0.7 in the morning to 1.7 in the afternoon [1].

Trajectories derived by the trajectory model of Deutscher Wetterdienst (DWD) based on archived three-dimensional pressure and wind fields from the DWD global model GME illustrate how air was uplifted from levels close to the desert surface in the central Sahara region (south and southwest Algeria and Mali) 4 to 5 days before its arrival at Lindenberg. It carried mineral aerosol to the middle troposphere (5 km elevation) over Central Europe. At that time, the high-pressure system 'Achim' resided over Central Europe with mostly cloudless sky and maximum temperatures above 30°C.

While pyranometer measurements at Lindenberg do not show an effect of the mineral dust plume on global irradiance in the VIS/NIR region, direct normal incidence irradiance (DIRNOR) decreased from the morning to the afternoon by 140 W m^{-2} at high solar zenith angle (SZA), and by 75 W m^{-2} at a SZA of 45°. Diffuse irradiance increased at the same time by 36 Wm^{-2} corresponding to 34 % at a SZA of 45°.

Different to the VIS/NIR region, global irradiance in the red part of the visible region (600 – 694 nm), as derived from spectroradiometric measurements, did decrease by about 7 % to 9 % from the morning to the afternoon. Similarly to the VIS/NIR, diffuse irradiance in the red region (600-694 nm) derived from Whole Sky Imager radiance measurements increased by 50 to 60 % from the morning to the afternoon.

In the UV region, global erythemal irradiance derived from spectral scans by a SPECTRO 320 D spectroradiometer also decreased from the morning to the afternoon by an amount corresponding to 0.4 UV index units. Diffuse erythemal irradiance, derived from spectroradiometric measurements with a sun shade, was almost not affected by the aerosol plume. The resulting direct erythemal irradiance at normal incidence was reduced by about 0.5 UV index units or 17.5 %. Similar changes as for erythemal irradiance occurred for VD3 effective radiation.

Radiative transfer model calculations using the LibRadtran model confirm the diurnal variation of the radiation components derived from different instruments for different wavelength regions. They show that the mineral dust appears to have had a much lower single scattering albedo (SSA) at shorter wavelengths in the visible and UV region (down to 0.62, see [2]) than at longer wavelengths in the VIS/NIR region, i.e. the mineral aerosol mainly absorbed radiation at shortest wavelengths.

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22 UV detectors based on zinc-oxide thin films

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The ultraviolet spectral range has become important for operations in various commercial, military and environmental applications: flame sensors, engine controls, source calibrations, secure space-to-space communications, UV astronomy and solar UV monitoring.

In the last decades the UV detection region has been covered essentially by exploiting silicon photodiodes and photomultiplier. UV silicon detectors are limited by 1.2 eV energy gap at room temperature, that means a low quantum efficiency in the deep UV spectral range, and by ageing degradation.

On the other hand, now it is possible to produce high performance UV photodectors based on wide band gap material like Zinc oxide. It is a member of the II-VI semiconducting compounds, it has a band gap ~3.4 eV and a large excitation binding energy of ~60 meV at room temperature, that make it promising both as light-emitted diode and as photodetector.

Istituto Nazionale di RIcerca Metrologica is involved in the activity on the ZnO UV detector development related to the Joint Research Project "Traceability for surface spectral solar ultraviolet radiation" (EMRP ENV03) which aim is to quantify decadal changes in solar UV radiation, measured at the Earth surface due to the expected changes in the global climate system.

ZnO photodetector have been realised both on film grown at INRIM by evaporation and post-annealed process and on commercial high-quality ZnO epitaxial film on sapphire substrates. The devices consist of two intergitated contact electrodes of aluminium fabricated through standard lithography and etching. The measured detector dark currents were too high, of the order of mA. An oxidation process has been carried out to both samples and resulted necessary to reduce the dark current of 3 orders of magnitude.

This work shows the characterisation of these photodetcors at several voltage biases and at different wavelengths. The responsivity could reach 10^3 A/W, but with response time on the order of seconds. At the moment these values limit the application of our detectors to slow acquisition times.

23 Realization of a UV fisheye hyperspectral camera

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We describe the design of a hyperspectral imaging system for the measurements of diffused sky UV radiance. To get this target a hyperspectral device developed at INRIM will utilize custom fish-eye UV collection optics to get an image of a wide portion of the sky. The device is based on an innovative hyperspectral imaging technique based on a scanning low finesse Fabry-Perot cavity associated to a Fourier transform based algorithm. The fisheye optics is based on a catadioptric scheme allowing a sky coverage almost equal to 2π. The instrument will be able to measure the UV spectrum of each pixel of an image (in the 320-400 nm range) recording a continuous sequence of frames in a single measurement. Each pixel of the hyperspectral image is associated to a portion of the sky. The device will ensure enough spatial and spectral resolution to improve cosine correction methods of existing solar UV spectroradiometers with conventional entrance optics, being able to map non uniformity of the spectral sky radiance (e.g. caused by clouds).

We will present the working principle, the detailed design, the simulations carried out for the realization of the prototype as well as the preliminary optic tests.

24 Upgrade of the New Zealand Urban UVB Network

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Since 1989 the Measurement Standards Laboratory (MSL) has been calibrating a network of erythemal UV sensors located across New Zealand, primarily at large centres of population. This paper describes a recent upgrade of this network and implementation of data processing algorithms which transfer data to the National Institute of Water and Atmospheric Research (NIWA) climate database.

The original UV sensors deployed were purchased from International Light Technologies Inc. and consisted of an SED 240 vacuum photodiode, interference filter and a ground fused silica cosine diffuser. This was mounted in a polycarbonate enclosure which also contained a circuit board with a transimpedance amplifier and 16 bit ADC, the output from which was read by a micro-controller and sent to an attached desktop computer. This PC then provided a VPN connection back to IRL where the data was collated.

More than 20 years of data was collected from these sensors but although this system was reasonably reliable, there were on-going maintenance issues. Hence with consideration also given to known sources of error in our measurements, such as lack of temperature stabilisation of the sensors and a spectral dependence of the angular response, the decision was made to upgrade the network with new sensors and data acquisition systems.

The replacement sensors purchased are Yankee Environmental Systems UVB-1 pyranometers, each with an accompanying UVPS-1 power supply. Each power supply unit has been modified in house with an updated DAQ board and ARM board style computer to meet the networks data logging and VPN connection requirements.

This new system has the following benefits:

- Desktop computer replaced by an embedded device, providing a low power alternative that is tolerant of power supply interruptions.
- Programmable gain amplifier circuit, allowing the gain to be increased for measurement of relative spectral response in the lab.
- Temperature stabilisation of the detector unit.
- More robust sensor unit for deployment outdoors.
- The sensor angular response is less dependent on variations in solar irradiance spectral distribution.

Additionally, data processing algorithms have been developed which transfer data from the sensors to NIWA at the end of each day. In combination with calibration functions forwarded to NIWA annually, daily data is converted to UV Index and uploaded to the NIWA climate database daily.

Work is ongoing to validate the data from these new instruments. A comparison was made between MSL and PMOD/WRC calibration functions for one UVB-1 instrument which highlighted interesting issues. This is still under investigation but further efforts to validate the data from the new instruments include keeping the old and new instruments co-located in Lower Hutt and Auckland and comparing measurements with NIWA instruments.

25 Novel micro mirrors based diode array UV solar spectrometer

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While diode array spectrometers can complete the acquisition of the entire UV solar spectrum in a few seconds, the portion of the spectrum below 300 nm is dominated by the stray light signal. The stray light originates from higher intensity radiation at longer wavelengths, which has a stronger influence on the signal on the detector pixels at wavelength regions with low irradiance levels. In conventional array spectroradiometer technology, the high dynamic range of atmospheric solar UV radiation (6 orders of magnitude between 290 nm – 440 nm) results in considerable bias during low intensity measurements. The main objective of a novel array spectroradiometer is to modulate the incoming solar UV spectrum to reduce the high variation of intensities before the light reaches the array detector. The optical design was carried out using Zemax with the main aim to preserve throughput of the optical system and to optimize its spectral resolution. The final design incorporates four spherical mirrors, a single flat reflective diffraction grating, the DLP chip and a back illuminated diode array detector (DAD). One feature of the design is the astigmatism generated by the use of off-axis spherical optics has been exploited by binning the DAD's vertical pixels, effectively using it as a 1-dimensional array.

To implement this concept, a novel micro mirror diode array spectrometer (μ-MUV) has been developed, which incorporates a micro mirror chip 1024x768 pixel XGA Texas DLP®. The purpose of the DLP is 2-fold: to select a portion of spatially dispersed spectrum from a diffraction grating, and utilize its high-speed switching to partially modulate the mirrors for reduced intensity in the spectrum of interest. This light is then re-imaged on to the diode array detector thereby filtering out the stray light components outside the selected range. All the optical components have been selected as off-the-shelf commercially available in order to reduce both the cost of the device and the procurement time in addition to simplification of prototyping. A prototype has been assembled to verify the validity of the base concept and initial measurements have been performed to confirm the throughput and image qualities such as spectral resolution. While the signal-to-noise ratio is poorer at visible wavelengths compared to commercial spectroradiometers, the ultraviolet region of interest demonstrates the intended stray light reduction when basic dlp-based light modulation techniques were implemented.

26 Improved Diffusers for Solar UV measurements

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Solar UV radiation scatters strongly in the atmosphere, and the diffuse component of the radiation accounts for a significant portion of the total UV radiation that reaches the surface of the Earth. To measure the total solar UV irradiance, the entrance optics of the measurement device needs to collect radiation from the entire hemisphere. This is typically achieved by using a shaped diffuser whose angular response, ideally, is proportional to the cosine of the zenith angle of the incoming radiation. Deviations from the ideal cosine response can cause significant errors in the results. In fact, the cosine error is one of the most important sources of uncertainty in solar UV irradiance measurements. The measurement data can be corrected, to an extent, if the angular distribution of the UV radiation at the time of the measurement is known. Unfortunately, this approach has a limited accuracy only, and the quality of the entrance optics remains of utmost importance for accurate global irradiance measurements.

We used a combination of measurements and simulations to optimize the cosine response of solar UV diffusers. At the first stage of the process, various material samples were measured for their diffuse transmittance properties in a goniometric setup to find out the most promising material candidate for use in an improved diffuser head. Quartz materials with gas bubbles that acted as scattering centers were found to be attractive alternatives to the traditional PTFE (polytetrafluoroethylene, Teflon) materials for this purpose.

Cost savings can be obtained when simulations are carried out before diffuser fabrication as compared to a purely trial-and error based diffuser optimization. For this reason, a Monte Carlo ray tracing algorithm was developed to simulate light propagation, scattering, and absorption inside the diffuser. The effects of the inner sidewall of the diffuser housing, the shadow ring, and the protective weather dome were also accounted for. The algorithm was validated by comparing measured and simulated results of the test samples. The algorithm was then used to optimize two types of detectors, one with a planar diffuser and the other with a spherically shaped diffuser. The integrated cosine errors of these detectors were calculated to be f_2 = 1.4 % and 0.66 %, respectively.

27 A collimated laser driven light source for the solar UV wavelength range

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For accurate measurement of the amount of solar UV radiation that reaches the earth, there is a need for improved calibration of spectroradiometers measuring the UV spectral irradiance of the sun. However, the spectral irradiance generated by an irradiance standard like a FEL lamp drops down rapidly for wavelengths below 400 nm, which hampers accurate calibration of UV spectroradiometers. We explore the possibility of using a commercial, portable laser driven light source (LDLS), which generates a broadband spectrum with a relatively strong emission in the solar UV range of interest (280 – 400 nm). The LDLS shows a high spatial and temporal stability of its emission. The combination of high stability and high spectral irradiance in the UV wavelength range makes the LDLS an interesting source for solar UV spectral irradiance calibration. The LDLS is a plasma-based source, which generates its emitted radiation in a small spherical volume (of diameter < 100 µm). This allows for efficient collimation of the emitted light. As a result, the spectral irradiance around a mean direction of propagation of the collimated beam is enhanced. The collimation also allows for efficient coupling through optical elements that provide a wavelength scale, like a Fabry-Pérot etalon or a birefringent wavelength ruler. We will present the latest results obtained with a collimated LDLS, compared to a FEL lamp and an uncollimated source.