Thematic Network for Ultraviolet Measurements

Abstracts for the workshop in Davos, July 15 – 16, 2014

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Acknowledgment

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1 Measurements of spectral sky radiance and its polarisation

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Knowledge of spectral sky radiance together with direct sun irradiance is a prerequisite for any detailed investigation of the effects of solar radiation at the earth's surface i.e. for exposure of humans or for characterising radiation on tilted surfaces for solar cells. Modelling of sky radiance with radiative transfer calculations suffer from the incomplete availability of all necessary input parameters, especially of the optical characteristics of aerosols. Therefore measurements are the necessary basis for such investigations.

With a double monochromator spectroradiometer with a field of view of about 1.5° scans of sky radiance as well as direct sun measurements are carried out since the 90's. Thereby the significant differences of the radiance distribution in dependence on aerosol amount and characteristics, albedo of the surrounding and altitude above sea level could be demonstrated. A different approach is the usage of all sky images with fish-eye lenses, which can provide high spatial and temporal resolution but limited spectral resolution. In order to get additional information about the optical characteristics of the aerosols, the double monochromator telescope as well as the imager is equipped with a polarisation filter. This allows determining degree and orientation of the polarisation of sky radiance for different wavelengths by taking measurements with different orientation of the polarisation filter.

Examples of measurements of spectral sky radiance and its polarisation under a large variety of conditions are discussed in combination with radiative transfer model calculations, demonstrating the effects of different atmospheric parameters.

2 UV research by simultaneous spectral radiance measurements

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The knowledge of the angular distribution of solar radiance and its spectral characteristics is required for many applications including solar energy and the impact of UV radiation on humans. Sky radiance has been found to be the dominant factor for the solar UV exposure of humans, both with respect to positive and negative effects of UV radiation. We recently developed a novel method to calculate vitamin D3–weighted exposure by integrating the incident solar spectral radiance over all relevant parts of the human body. Earlier investigations are based on the irradiance on surfaces, whereas our calculated exposure of a voxel model of a human takes into account the complex geometry of the radiation field. Our calculations show that the UV index is not a good indicator for the exposure which depends on the orientation of the body [e.g. vertical (standing) or horizontal (lying down) posture]. At the winter solstice vitamin D3 cannot be obtained with realistic clothing even if the exposure were extended to all daylight hours. Since clouds play a crucial role in determining the actual exposure of humans and the yield of solar cells, new instruments that measure sky radiance in dependence of zenith and azimuth angle in more than 100 directions simultaneously have been developed in recent years. Such instruments are expected to improve our understanding with respect to both solar energy and health effects of solar radiation.

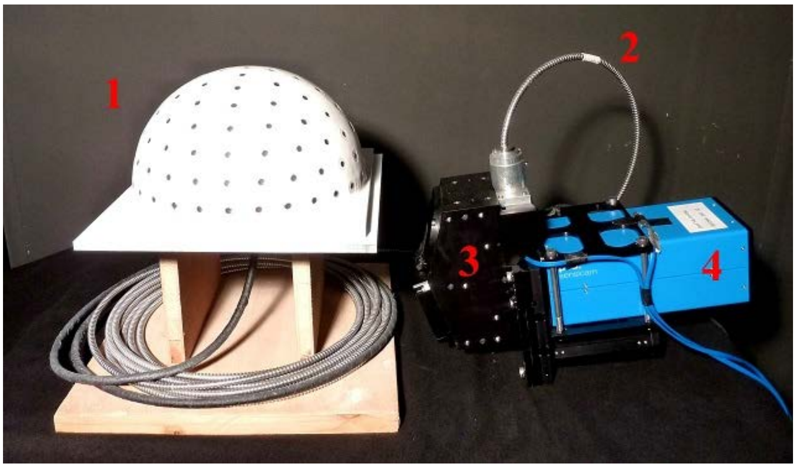

Figure 1. Main components of MUDIS: hemispherical entrance optics dome with weather protection (1), fibre bundle (2), Offner imaging spectrometer (3), UV-sensitive CCD camera (4).

The developed spectroradiometer is shown in the figure above. The main component of MUDIS is a hyperspectral imager consisting of a UV-sensitive CCD camera and an Offner imaging spectrometer. A bundle of optical fibres are embedded in a hemispherical shaped dome and are evenly distributed in zenith and azimuth directions. A single measurement (sky capture) performed with MUDIS therefore simultaneously performs 113 sky radiance measurements in different zenith and azimuth directions. MUDIS is capable of measuring spectra from 250 to 600 nm with a bandwidth of approximately 2 nm and a sampling interval of 0.4 nm.

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3 Suitability of a Fourier Transform Spectroradiometer as a reference instrument for Solar UV Irradiance Measurements

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The suitability of a commercially available Fourier transform spectrometer (FTS) as an alternative reference spectroradiometer for solar UV irradiance measurements has been examined within the European Metrology Research Project ENV03 "Traceability for surface spectral solar ultraviolet radiation". Fourier transform spectrometers have specific advantages (in particular high throughput, simultaneous and fast measurement of the whole spectrum, inherent traceability and high accuracy of the wavenumber scale [1, 2, 3] which may help to improve the dissemination of absolute irradiance scales to remote measuring sites.

As a first step, it has been investigated whether semiconductor UV detectors (Si and GaP) can be used within the FTS (Bruker FTS VERTEX 80v) because this type of detectors has a comparatively high stability of the spectral responsivity. However, it was found that these detectors are only usable down to wavelengths around 360 nm for absolute solar UV irradiance measurements despite the high throughput (Jacquinot or throughput advantage) of the Fourier transform spectrometer because of the large losses of radiant power within the global entrance optic. Consequently, a photomultiplier tube (photosensor module H10723-210 with bialkali photocathode from Hamamatsu) has been applied and characterized for the use within the FTS. The spectral range of the spectroradiometer has been confined to the desired wavelength range from 280 nm to 400 nm by using different optical bandpass filters. A calibration of its spectral irradiance responsivity has been performed against a high temperature blackbody radiator (HTBB pg3200, [4, 5]) and a secondary irradiance standard (halogen lamp) which was calibrated against the national irradiance standard of the PTB [6].

Beside the measurements of the spectral irradiance responsivity, the investigations have included the determination of the uncertainty of the calibration measurements and of solar UV irradiance measurements. Finally, a solar UV comparison measurement against the current reference instrument QASUME [7] – a scanning spectroradiometer – has been performed.

The results of the investigations will be presented. This will include a discussion of advantages and disadvantages of the use of an FTS as a reference instrument for solar UV irradiance measurements.

Acknowledgement

The authors thank Peter Sperfeld and Klaus Anhalt from PTB for their support and the providing of the irradiance sources.

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4 Realization of Improved Solar UV Diffusers

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As solar UV radiation scatters strongly in the atmosphere, an instrument that measures the global solar UV irradiance needs to collect radiation from the entire hemisphere. In the ideal case, the angular response of such an instrument is proportional to the cosine of the zenith angle of radiation and independent of the azimuth angle of radiation. Deviations from the ideal cosine response can cause significant errors in the results, and the cosine error is one of the most important sources of uncertainty in solar UV irradiance measurements. Therefore, the quality of the entrance optics remains of utmost importance in solar UV measurements.

Shaped diffusers are commonly used at the entrances of global irradiance measuring instruments to reach near-ideal angular responses. Optimizing the dimensions of the diffuser assembly through trial-and-error prototyping can be very tedious and expensive. For this reason, we have developed a Monte Carlo ray tracing algorithm for simulating radiation transport inside the instrument. The algorithm can be used to guide the diffuser design process as well as to investigate how sensitive the angular response of the diffuser assembly is to changes in the parameter values. This latter feature is important when manufacturing tolerances need to be considered.

In the project, two diffuser prototypes were constructed: one with a fiber connector and the other to be used with the Brewer spectroradiometer. In both cases, the diffuser element was made of synthetic quartz material with small gas pockets. The diameters of the planar diffuser elements were 11 mm and 22 mm for the fiber and Brewer devices, respectively. A protective weather dome was incorporated in both structures. For the first prototype of the new diffuser assembly for the Brewer spectroradiometer, the measured integrated cosine error was f_2 = 2.3 %. For the second prototype of the diffuser assembly with the fiber connector, the measured cosine error was f_2 = 1.4 %.

5 Application of a dual-channel solid state spectrometer to measure spectral surface radiation and atmospheric constituents

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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.

In this study a two-channel solid state instrument covering the UV and visible wavelength ranges, one channel measuring global irradiance and the other measuring the direct solar component via attachment to a suntracker, was deployed 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.

The retrieved total ozone column data from a period of over a year 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. In particular we focus on the following aspects: (1) instrument stability during the monitoring period, (2) improved stray light correction and its effect on the retrieved TOC, (3) appropriate choice of absorption spectra and details of retrieval algorithm including the contribution of other absorbing constituents. Additionally two different data acquisition methodologies, both designed to overcome the limitations of the instruments' low dynamic range, are compared – continuous averaging at short integration times used in the first part of the study and adaptive choice of integration time during the latter part.

6 Overview of observations made as part of the EMRP ENV03 Solar UV project.

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As part of the EMRP project two array spectrometers were deployed for varying periods from May 2013 until June 2014 in Manchester to measure the direct and global solar irradiance. There are several advantages in using array spectrometers such as having large wavelength ranges measured simultaneously with short integration times (< second) and also mechanical stability due to having no moving parts. They are also less expensive than scanning instruments but due to limitations inherent in the layout of the monochromator and the detectors these instruments suffer from poor quantum efficiency in the UV and problems due to stray light. This means that calibration and analysis of measurements is not as straightforward as for scanning spectroradiometers.

To help in the development of calibration routines to improve stray light correction and allow the instruments to be used to their theoretical limits the instruments were rigorously characterised in the laboratory before deployment and when in operation a Bentham DTM300 scanning spectrometers was used to measure spectral data at (approximately) the same time and location as the array spectrometers. The characteristics of the array spectrometers used in this project are then compared to the list of the recommend specifications for such instruments(1) and the effect of the instrument limitations and differences between the two arrays are discussed.

An overview of the data obtained during the project in Manchester will also presented in this poster, and then the results of seasonal and diurnal variation in the range of wavelengths of the array spectrometers is presented along with the effects of stray light correction on the spectral data. The results show that with the use of correct operating procedures array spectrometer are able to make a useful contribution to solar observations, with the main limitation being the lower wavelength limit due to low quantum efficiencies in the UVB.

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7 Improvements implemented and preliminary characterisation of Avantes CCD spectrometer at INTA - "El Arenosillo" in Huelva, Spain

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Array spectroradiometers can measure an entire solar UV spectrum at once but scanning spectroradiometers are still the standard references in terms of accurate radiation measurements, especially at the shortest UV wavelengths. Although scanning spectroradiometers are the most accurate instruments, they suffer from some disadvantages: high cost and demanding maintenance, susceptibility to movement and speed of operation. In contrast, array spectroradiometers offer reduced cost and more rapid data acquisition but present some drawbacks due to stray light contamination, reduced response at short wavelengths, and short dynamic range. An Avantes array spectroradiometer has been recently installed at INTA - "El Arenosillo", in Huelva, southwestern Spain. This new instrument consists of two spectroradiometers, an Avantes AvaSpec-ULS2048XL-USB2 for measuring solar radiation from 280nm to 440nm and one Avantes AvaSpec-US2048L-USB2 to measure solar radiation from 440nm to 940nm. This combination of spectroradiometers can solve the problem of short dynamic range. In order to improve solar global measurements, a Schreder J1002-SMA-111 diffusor has been installed at the fiber optic entrance. To reduce the stray light in the spectrometer when measuring UV radiation, a low pass filter was installed before the entrance slit of the instrument. To improve the performance of this filter the distances between optical elements had been reduced. The manufacturer provided a relative calibration in wavelength but an absolute calibration is needed. Thus, the spectroradiometer has been calibrated with respect to a DXW 1000W certificated lamp in order to obtain absolute calibration, and using discharge lamps in order to test the calibration in wavelength. Once calibrated, the instrument has been installed on the observatory terrace. Preliminary results are presented and compared against a well calibrated double Brewer spectroradiometer.

8 Comparison of 400 nm and 450 nm filters for reducing the stray-light in UV measurements with an Avantes CCD Array Spectrometer at INTA - "El Arenosillo" in Huelva, Spain

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CCD array spectroradiometers measure radiation over a wide range of wavelength covering the complete solar spectrum. Recently, these instruments have experienced a notable development and their applications in meteorology studies have notably increased.

In fact, they are becoming more and more popular as a reliable alternative for the highly demanding scanning spectroradiometers. However, these new instruments present some drawbacks which must be addressed before becoming standard instruments for a general use.

One interesting use of this kind of spectrometers is the accurate measure of spectra in the UV (ultraviolet) wavelength range. A major limitation for this aim is due to the contamination by stray-light coming from longer wavelengths. Different solutions have been proposed to fight against this drawback. One of them consists of interposing filters between the diffuser and the entrance slit of the spectroradiometer.

In this study, 400 nm and 450 nm filters have been used in order to eliminate the stray-light in the Avantes AvaSpec-ULS2048XL-USB2 recently installed at the INTA – "El Arenosillo" Sounding Station in Huelva (Spain). The filters have been placed between the diffuser and the spectroradiometer entrance slit. In order not to loose much signal intensity, the standard filter holders have been modified and a fused silica ball lens has been added. Once completed the setting up, the 400 nm and 450 nm filters have been essayed and different actual spectra have been measured at the El Arenosillo terrace, under different sky conditions. This study presents the results obtained with both filters, its comparison and the performance achieved by using this technique.

9 Development of an array spectroradiometer with improved stray light rejection using band-pass filters

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Solar UV irradiance measurements (280 – 400 nm) require specific measurement conditions because of the rapidly varying Sun irradiance level on the 10 s time scale. Array spectroradiometer is potentially a good instrument that can meet these requirements. However these spectroradiometers suffer from stray light that can lead to large error in the short wavelength UVA range (280 – 300 nm) of the Sun spectral irradiance. Stray light can be characterized (SLF spectral line-spread function method) using a tunable 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 SLF characterization. Therefore a reduction of the stray light contribution is necessary to improve the solarUV irradiance measurement uncertainty.

In the framework of the ENV03 project task 4.4, we propose to use band-pass filters to reduce the spectral bandwidth of the incoming light inside the spectroradiometer and hence reduce the stray light contribution. The modified spectroradiometer is based on a Jobin Yvon VS140 array spectroradiometer optimized for UV operation. The measurement spectral range is 200 nm-650 nm. The spectral bandwidth is about 1 nm on the 280 – 400 nm spectral range. The spectroradiometer is fitted with a 600 µm diameter 1x2 optical fiber. The two input fibers are connected to two cosine response diffuser heads equipped with dedicated filter. The first head is equipped with an interference filter (central wavelength of 290 nm and a spectral bandwidth of 30 nm) and a 3 mm thick UG11 type filter and is operated on the 280 – 305 nm spectral range. The second head is equipped with a 0.5 mm thick UG11 type filter and is operated on the 305 – 400 nm spectral range. The spectroradiometer is put in a thermal box for controlled temperature operation.

We present first the characteristics of the spectroradiometer and the characterizations performed: transmission of the filters, linearity, temperature behaviour, stray light (SLF), spectral calibration, noise level, measurement stability… Then we will show the results of the comparison that will take place in Davos in July 2014 and the uncertainty budget.

10 Radiometry of UV LED arrays for cell culture irradiation

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The Dosimetry Laboratory conducts activities in the area of radiometry, to cover ultraviolet, visible, and infrared radiation measurements, including characterization of laser and LED systems for medicine and dentistry. Our group has also been searching for sources with application in photochemistry and, more recently, spectral radiometry of solar ultraviolet radiation, aiming at photodynamic therapy of plant-pathogenic fungi.

UV LED home-made arrays employing high-brightness units are a recent option for research areas that need a low-cost and feasible light source for cell culture irradiation. Characterizing such units is one of the objectives of the Laboratory, and this work will show a sequence of measurements that will characterize the stability of the irradiance value along irradiation and the spatial homogeneity of the irradiance over the surface of a 96-well microtiter plate. The spectral power [W/nm] was measured with a calibrated spectroradiometer (CDS 610, Labsphere) coupled to an integrating sphere (LMS 100,LabSphere) with 10-inch diameter. The spectral irradiance of the array was analyzed with a calibrated spectroradiometer (USB2000, OceanOptics) coupled to an optical fiber and cosine corrector.

For a 96-well microtiter plate, 200 UV LED units (VAOL-5EUV8TH, VCC) with emission at 385 nm were purchased. The spectral power of each led was measured individually by introducing the LED into the integrating sphere. For the device construction, 96 LEDs with the nearest emitting power to that of the mean value were selected. After the LED array construction, the device was mounted under a 96-well microtiter plate and each well was measured individually with the cosine correction probe placed inside the well. Considering 24-hour intervals, three repetitions were conducted.

Figure 1 shows the mean values of individual wells for all 96 LEDs. It is possible to observe a faulty LED with only 4.059 µW/cm2/nm and a range of values for different colors. The mean value of all the 96-well microtiter was 8.171 ± 175 $\mu W/cm^2/nm$ (s = 1.714 $\mu W/cm^2/nm$). The maximum value registered for a well was 12.627 $\mu W/cm^2/nm$, three times higher than the lowest measured value. This difference shows how extremely individual wells can vary. The time stability of the irradiance was measured over an interval between 1 min and 2 h. The time constant varied between 8.2 and 15.9 min for 10 wells. This corresponded to an irradiance change of 63.2% (1-1/e) for a stable irradiance. If a change of 86.5% (1-1/e2) is considered, twice the time is necessary, i. e., for a more stable irradiance, the device must be turned on at least 30 min before use.

This work recommends the selection of LED units with similar power irradiance before the LED array is mounted, a spectral irradiance measurement conducted on a yearly basis, and the use of the device only 30 min after it is turned on. The conclusions of the present work can be also applied to other LED devices emitting in the visible spectral range.

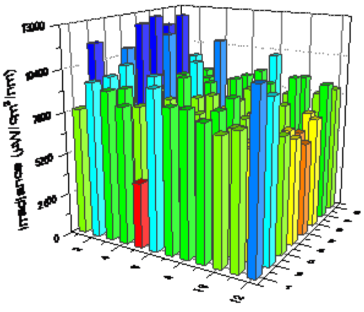

Figure 1. Mean values of irradiance from individual wells of a LED array for 96-well microtiter plate.

11 Solar exposure and influencing parameters on the endogenous vitamin D production

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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 was 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 of the research project 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. In each case, 6-fold of the skin area (whole body exposure) compared to the irradiation of face and hands lead to only a 3-fold 25OHD3 serum level increase – in contrast to the assumptions the literature.

In a further study we could prove our hypothesis, that the skin of the several anatomical location presents a different effectiveness in the UV-induced vitamin-D-production. This was the explanation of the mistake in the above called assumption. Face on one hand and back of the hands on the other have the same skin area. Furthermore, the solar UV-exposure levels of face and hands are comparable. But in a long-sleeved person 80 % of 25OH3 increase would be caused by the solar face exposure – the rest by the hands. In a short-sleeved person the face contributes 60 % vs. 40 % from hands and arms.

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

12 Essential minimum textile and dermal protection factors for outdoor workers – a safety concept for solar exposed workplaces in the mid-latitudes

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For the 8 h-workday at workplaces with the risk of exposure by artificial UV-sources the ICNIRP recommended spectral threshold values (taken over e. g. by the EU-Directive 2006/25/EC "Artificial Optical Radiation"). This spectral threshold values are an "artificial action spectrum" that envelops action spectra of the acute UV injuries to the eyes (photoconjunctivitis, photokeratitis) and to the skin (UV-erythema) with a safety factor 2.5 to 3 for the 8h-workday. The basic consent of the ICNIRP safety concept is that UV-exposures less than 30 % of the acute reaction threshold would not result in chronic effects – even if repeated every 24 h.

Basing firstly on this ICNIRP safety concept to repeated UV-exposures of workers and secondly on analysis of the real solar UV-exposure conditions of outdoor workplaces we propose minimum requirements on the ultraviolet protection factor (UPF) of closing worn by outdoor workers and SPF of dermal skin protection[*)].

In practice, organizational measures or/and technical measures to reduce solar UV-exposure at outdoor workplaces are often not possible to realize. Therefore, closing, cap and sun protection glasses have the function of individual protection measures.

Depending on (a) the real UV-exposure per workshift, (b) the body distribution of the solar radiation and (c) the body distribution of the skin sensitivity to UV-radiation: we determined for different body sites minimum required UPF for textiles covering the skin areal as well as the SPF for uncovered skin areas, to realize UV-exposure in each skin area less than 30 % of the MED. To derive the UV-exposure data per workshift we analysed half hour erythema dose datasets (2000-2008) of seven stations of the German solar UV-monitoring measurement network (sUVMonNet). The body distribution of solar UV-exposure of outdoor workers was measured under real working conditions seasonally in previous research projects. The erythemal skin sensitivity was derived from literature and own experience in photodiagnostics.

In the mid-latitudes (45°-60° N; Germany: 47°-55° N) for the body sites a erythemal UV-exposure < 30 % MED (skin type II) requires at least UPF: 20 (chest, back), 50 (shoulder), 6 (thigh) and for uncovered skin parts (repeated) SPF: 20 (face, neck, nape) and 10 (hands, arms, legs).

[*)] German Federal Institute of Occupational Safety and Health (BAuA) support-N° F2036 – Research project: "Protection components to reduce solar UV-exposure of outdoor workers"

13 Stray light correction of array spectroradiometers for solar UV measurements

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Due to the parallel mode of operation, compactness and affordability, array spectroradiometers are increasingly used to monitor solar radiation. In order to ensure measurements with acceptable uncertainties, however, the instruments have to be carefully characterised and calibrated. In the solar UV spectral range, the measurement uncertainty is dominated by an uncertainty contribution caused by a poor suppression of the internally created stray light. To handle the spectral stray light problem, various approaches exist in terms of both hardware implementations, e.g. blocking filters, and mathematical correction procedures based on careful instrument characterisations.

The stray light corrections determined from results of the line spread function (LSF) characterisations are effective as long as either the spectral range of the instrument covers the spectral range of the array detector, typically a silicon-based charged coupled device (CCD), or radiation outside the spectral range of the spectroradiometer is prevented from getting into the instrument. A typical silicon detector is sensitive to the optical radiation at wavelengths of up to about 1100 nm. Hence, a stray light correction matrix determined for an array spectroradiometer having its spectral range limited to, e.g., wavelengths from 200 nm to 400 nm would not be capable of completely correcting the spectral stray light unless additional measures are taken to account for the stray light that is created outside of the spectral range of the spectroradiometer. Obviously, the simplest way of taking care of this, let's call it out-of-range (OoR), stray light would be the use of bandpass filters or other spectral pre-selection techniques. However, as hardware modifications are not always desired, it is also possible to characterize the response of the instrument to the OoR radiation and to take it into account by a matrix for the OoR responsivity. In contrast to the normal LSF characterisation procedure, however, an additional calibrated instrument is needed as a reference for the OoR radiation measurements during the characterisations. A prerequisite for the application of the correction for the OoR stray light is knowledge of the irradiance at the OoR wavelengths both during source-based calibration of the instrument and solar measurements.

In this talk we present such a work that has been carried out within the EMRP project "Traceability for surface spectral solar ultraviolet radiation". The aim of the respective task was to characterise and correct spectral stray light of array spectroradiometers, including the stray light caused by the OoR radiation. We will also share results of the stray light characterisations carried out on different instruments within the EMRP project using a wavelength-tuneable laser setup at PTB.

14 Characterisation of nonlinearities of array spectroradiometers

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As part of the EMRP ENV03 project, various setups for characterizing nonlinearities of array spectroradiometers were developed, tested, applied, and intercompared. The terrestrial solar UV irradiance varies over 5 to 6 orders of magnitude, in the relatively narrow spectral range of 280 – 400 nm, the maximum irradiance being approximately 1 W m^{-2} nm^{-1}. This range was used as the goal for all setups.

At PTB, the wavelength tunable laser facility (TULIP) was extended into the solar UV spectral range by frequency doubling and tripling of a mode-locked Ti:Sa fs-laser [1]. A beam conditioning unit was developed providing a stable, depolarized, spectrally narrow and spatially uniform irradiance field for linearity characterizations. A specially designed fiber bundle used within the beam conditioning unit acts as a pulse-to-continuous wave (CW) converter. Spectral irradiance level can be set and attenuated by a variable filter.

A similar setup, a frequency doubled and tripled Ti:Sa ps-laser with 80 MHz repetition rate, is used at METAS. The quasi CW ps-radiation is stabilized with a liquid-crystal modulator (LCM) and a monitor detector. The beam is directly applied to the entrance optics of the spectroradiometer. The power level is changed by adjusting the working point of the LCM and by adding attenuation filters.

Aalto built a setup based on a single monochromator with two alternative light sources; A 500-W Xe-lamp and a 1-kW Hg-lamp. The light exiting the monochromator is collimated and attenuated with interchangeable filters. The light beam then continues to the device to be characterized through a beam splitter taking a fraction of the beam on to a S1337 photodiode serving as the linearity reference [2].

VSL developed a portable, mobile system, for in-situ characterization of spectroradiometers. The device combines two linear polarizers, whose reciprocal transmission axes can be set to any angle by a rotation mount, a 2” averaging sphere, and a Si detector at one of the output ports of the sphere acting as the linearity reference. The device under test can be mounted at one of the other sphere output ports. The system is powered by a UV laser at 372 nm but in principle, other sources can also be used.

This presentation will show more details and properties of the setups developed and the results obtained. The setups of VSL, PTB and Aalto are currently being intercompared by characterizing two array spectroradiometers with all setups.

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15 A Laser-Driven Light Source (LDLS) as a portable spectral irradiance calibration source in the UV range and other radiometric applications

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An important requirement of any accurate experiment is to be under statistical control. This means that once the aimed uncertainty, u say, for the quantity of interest is specified, one has to guarantee that the signal to noise ratio (*SNR*) of the measured quantity stays always roughly larger than$1/u$.

For accurate measurements, this sets quite stringent requirements on the minimum values for the signal to be measured. Calibration measurements do not represent an exception in this sense. For this reason, in many radiometric applications it is highly desirable to have available light sources which show excellent temporal stability and high spectral irradiance (or spectral radiance, depending on the specific application) levels and that, possibly, are still not too complex to operate in practice.

In this context, 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 range 280 – 400 nm which makes them of special interest for calibration of spectroradiometers for measurements of the UV component of solar radiation reaching the Earth.

In this work, we will discuss the main properties of one such light source, a Laser-Driven Light Source (LDLS) and how it can be employed as a spectral irradiance calibration tool. Additionally, other applications of the same source are also discussed, such as the characterization of responsivity of detectors through monochromator-based radiometers.

16 Novel micromirror device based diode array UV solar spectroradiometer

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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 micromirror device in an array spectroradiometer enables precise selection of the desired wavelengths, as well as the ability to reduce spectral intensity via selective mirror modulation, both reducing long wavelength stray light. A prototype consisting of off-the-shelf components has been assembled within the European Metrology Research Project ENV03 "Traceability for surface spectral solar ultraviolet radiation" 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 and astigmatism.

The high dynamic range of the atmospheric solar UV radiation (approx. 6 orders of magnitude depending on the 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 [1]. In a previous study [2], it was demonstrated via libRadtran modelling [3] that there is a 4 orders of magnitude stray light contribution from wavelengths above the UV range of interest (290 nm to 440 nm) that would interfere with an accurate UV spectral intensity measurement. Furthermore, implementing a digital micromirror 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 [2,4]. While the use of DMD’s in spectroradiometer applications has been previously explored for visible light [5–7] and infrared applications [8], in this study, a novel micromirror 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 [9].

The key elements of the model and the subsequent prototype consist of a plain ruled 600 G/mm diffraction grating, a 1024 x 720 pixel XGA DLP micromirror chip, a back-lit 2048 x 250 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. In comparison to commercially available spectroradiometers, the μ-MUV prototype has a wider slit function and poorer spectral resolution but is capable of reducing stray light via modulation techniques as predicted. Future work includes construction of a light-tight enclosure and wavelength specific modulation to further explore dynamic range levelling.

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17 Characterisation of TE-cooled array spectroradiometers for solar UV measurements

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Two TE-cooled CCD array spectroradiometers were considered for solar UV measurements: an Ocean Optics QE65000 (TEC=-10C) and a B&WTex Glacier X (TEC=+14C). Results of thermal relaxation to changing ambient temperatures and its effect on dark signal, sensitivity and wavelength shift will be presented; together with options for dark signal determination and linearity of the instruments within their operation range. Testing of practical methods of stray light correction by inter-comparison with a scanning double-grating instrument and implications of limitations of the tested instruments on field measurements will be discussed.

18 Monte Carlo technique applied to the uncertainty evaluation of spectral irradiance measurement using array spectroradiometer

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Array spectroradiometer are used to measure spectral irradiance of sources in many applications. However accurate measurements require a proper characterisation of the spectroradiometer: wavelength scale calibration, linearity, time integration calibration, stray light, cosine response, dark signal, etc. The spectroradiometer needs to be calibrated prior to any measurement, and this calibration is also dependent upon the above characteristics. Therefore correlations between inputs quantities have to be taken into account. Furthermore the output quantity is non-linear with respect to the input quantities.

Monte Carlo technique has been proven very powerful to evaluate the uncertainty of an output quantity that depends nonlinearly with the input quantities. Then such technique should be used to evaluate the uncertainty associated to spectral irradiance measurement. The critical part of this technique is the complete definition of the measurement model.

In the framework of the ENV03 project task 2.2, we have developed software to evaluate the uncertainty of solar UV irradiance measurement using an array spectroradiometer. This software is based on the Matlab algorithm. Monte Carlo technique is easy to implement, as the Matlab tools are validated according to supplement 1 of the GUM 98-3.

We present first the measurement model that takes into account the calibration of the spectroradiometer with a standard lamp, and all the corrections associated to the characteristics of the spectroradiometer, including the stray light correction based on the matrix obtained from the SLF (spectral line-spread function) characterisation. Then we show how Monte Carlo technique is implemented through the different steps from the calibration process to the solar UV measurement process. Example of uncertainty evaluation of spectral irradiance measurement using array spectroradiometer developed within the ENV03 project is presented.

19 Source-Based and Detector-Based Calibration of QASUME at PTB

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INTRODUCTION

Quality assurance of the solar spectral ultraviolet radiation measurements at the European UV monitoring sites and harmonisation of the results are based on the portable reference spectroradiometer, QASUME, operated by the Physikalisch-Meteorologisches Observatorium Davos/World Radiation Center (PMOD/WRC) [2]. The calibration of the QASUME spectroradiometer is carried out via a set of transfer standard lamps traceable to the spectral irradiance scale at the Physikalisch-Technische Bundesanstalt (PTB) which itself is realized by a high temperature blackbody [3, 4].

One of the goals 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. Therefore several measurements and intercomparisons have been performed on QASUME at the PTB.

FROM SOURCE- TO DETECTOR-BASED CALIBRATION

The traceability chain for the calibration of QASUME reference spectroradiometer is mainly source-based: a high-temperature blackbody radiator as primary standard of spectral irradiance and transfer standard lamps are used for direct or subsidiary measurements (Figure 1, right side). Alternatively, a completely detector-based traceability chain allowing a calibration of the spectral responsivity of QASUME against a trap detector can be realised with the help of wavelength-tuneable lasers (Figure 1, left side). The motivation to follow this new traceability route was to shorten the traceability chain to the primary standard of optical power, the cryogenic radiometer, and, thus, reduce the associated uncertainties.

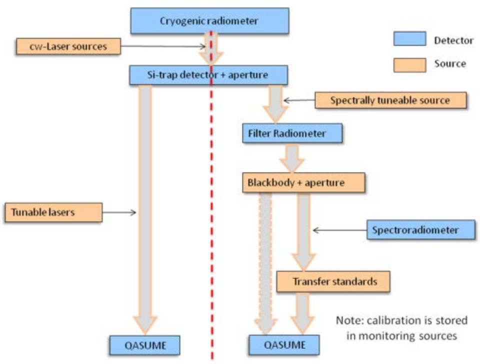

Figure 1. Traceability chain for the calibration of the reference spectroradiometer QASUME: it can be realised by means of calibration sources as shown to the right from the vertical line or by using a calibrated detector and wavelength-tuneable lasers.

Within the framework of the EMRP solarUV project, the wavelength-tuneable laser facility at the 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, several enhancements from laser stabilization to beam conditioning for the irradiance mode has been developed (see Figure 2). The traceability to the primary standard for radiant power, the cryogenic radiometer of the PTB, is provided by silicon trap detectors built and characterised for this purpose. The transfer to irradiance responsivity has been realized using a radiometric aperture with calibrated area.

Two measurement campaigns involving both the calibration of QASUME spectroradiometer at the TULIP facility against the trap detectors and a direct measurement of spectral irradiance by the 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 calibrations will be presented during the talk.

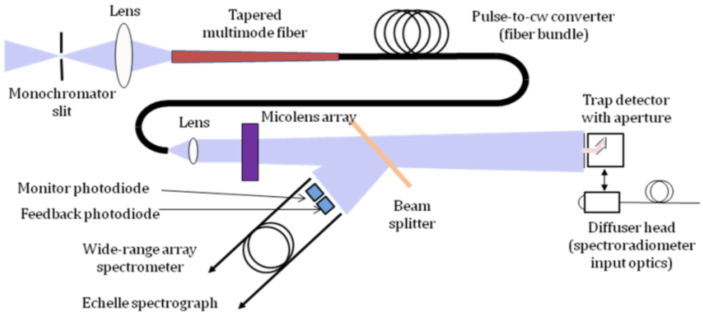

Figure 2. Schematic representation of a beam conditioning unit in the TULIP facility used to convert the beam of a mode-locked fs-pulsed tuneable laser into a uniform, stable and depolarised radiant field necessary for the irradiance-mode calibrations.

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20 Multi-spectral fisheye camera for UV sky radiance measurement

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We present an instrument to measure spectral irradiance of sky, based on a multispectral camera and a fisheye cata-dioptric imaging system. The purpose of the prototype is to improve the traceability of UV radiometers to SI units. The existing instruments observe the 2π emissivity of sky in the UV region (300 – 400 nm wavelength) through an integrating entrance optics and measure the total irradiance. This parameter is particularly important for monitoring skin cancer risk. Traceability of such instruments to SI units is so far not guaranteed. Dependence of entrance optics with angle (cosine effect) and environmental variables, such as presence of clouds, seriously affect the accuracy of UV radiometers. In order to measure the corrections and to implement a valid model of the emissivity of the sky measured by radiometers, it is important to realize an instrument to be used as a reference which collects as much information as possible of the spectral and spatial distributions of the sky irradiance.

In the framework of the European Metrology Research Program (JRP ENV-03 Solar UV), we have realized a camera, based on a large convex spherical mirror coupled with a quartz lens objective and a special CCD sensor, capable of observing the whole sky (up to 83° zenith angle). The spatial resolution is better than 1 square degree per pixel. A filter wheel made with 11 band pass filters allows 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.

The realization of the camera, field tests, and the calibration of the camera with a reference spectro-goniometer will be described.

21 QASUME II – the new portable solar UV reference spectroradiometer

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A new reference spectroradiometer QASUME II was constructed within the European Metrology Research Project ENV03 *"Traceability for surface spectral solar ultraviolet radiation"*. The principle design of the instrument has been copied from the current European reference instrument QASUME [1]. The core part of both systems is a Bentham DM150 double monochromator. However, the entrance optic of the old instrument deviates slightly from the nominal cosine response, which leads to diurnal variabilities of up to ±1.5% during solar irradiance measurements. The photon detector, a photomultiplier tube (PMT), shows hysteresis effects after illumination which add to the uncertainties of the measurements.

The two main disadvantages of the reference instrument could be overcome by the development of two new state of the art components. These devices were constructed within the Work Packages 3.1 and 4.2. The PMT was replaced by a Solid State Hybrid Detecting Device (SSDS) [2]. It consists of Silicon diodes coupled to a high sensitive readout electronic. These diodes have on the one hand an outstanding stability and on the other a low sensitivity in the UVB wavelength range. The SSDS was therefore equipped with a small commercial prototype USB photo counter by Hamamatsu. The hybrid system has now the same high sensitivity as the old QASUME PMT while performing as a stable reference detecting device. The second improvement was the replacement of the input optic. The Teflon diffusor of the old optic was replaced by a new diffusing quartz material [3, 4]. An important improvement is the negligible change of its transmission as a function of the temperature and humidity, which is a severe problem with Teflon diffusors. In addition the design of the optic is currently being optimized for an ideal cosine response.

After the construction of QASUME II the system was validated against the European reference instrument. The operating mode of the SSDS was developed during solar UV measurements. The system was characterized in the laboratory to derive its slit function, dispersion relation, cosine responsivity, azimuth error, etc.. The long term stability and performance of QASUME II was invested during outdoor measurements parallel with the QASUME.

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22 Post processing of data from array spectroradiometer

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Array spectroradiometers are able to measure an entire solar UV spectrum within integration times between milliseconds and seconds. The post processing of array spectroradiometer data needs a specific procedure to obtain reliable and comparable measurements.   Based on the experimental experience of a commercially available and with a DUG11X modified array spectroradiometer - Avantes AvaSpec-ULS2048x14 an exemplary post processing method was elaborated:

The dark measurement, taken right before each sun measurement, was subtracted from the raw data to get the raw signal (quantified in counts).

The raw signals from measurements with 2 different integration times was converted to counts per millisecond and merged to one spectrum eliminating the saturated pixels.

Each merged spectrum (in counts) was corrected for straylight using the straylight correction matrix derived from a tuneable laser facility.

The data was converted to irradiance using a responsivity derived from calibrated lamps in the laboratory at PMOD. The responsivity was also corrected for stray light using the same stray light correction matrix as for the sun measurements.

The continuously measured spectra were aggregated (average) to a defined regular time span (1 min.).

The aggregated spectra were corrected for wavelength shift and the bandwidth was homogenized to a regular bandwidth and a regular wavelength grid using the new developed MatSHIC software. The new software is able to use the variable slit function to produce homogenized spectra on freely selectable wavelength grids.

In order to compare data from array-spectroradiometer with data from scanning doublemonochromator, where each wavelength is measured step by step, a time-synchronization procedure is developed. The procedure selects data from the array-spectoradiometer which is closest to the measurements of the scanning instrument - in wavelength and time.

The presented method of post-processing – in particular the software MatSHIC may be applied for other array spectrometers. Possible modifications of the presented procedure is discussed.

23 A precision solar spectroradiometer for spectral aerosol optical depth and solar irradiance measurements

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The radiative forcing of atmospheric aerosols represents one of the largest uncertainties in the Earth radiative budget. Global networks of surface based sunphotometers such as the GAW-PFR network operated by PMOD/WRC measure the aerosol optical depth at several distinct wavelength channels between the ultraviolet and the infrared. A precision solar array spectroradiometer has been developed in order to complement and eventually replace the four-channel precision filter sunphotometer currently in use.

A new generation of solar spectroradiometers, the Precision Solar Spectroradiometer (PSR), has been developed at PMOD/WRC to eventually replace current filter based sunphotometers (see Figure 1). It is based on a temperature stabilized grating spectroradiometer with a 1024 pixel Hamamatsu diode-array detector, operated in a hermetically sealed nitrogen flushed enclosure. The spectroradiometer is designed to measure the solar spectrum in the 300 to 1020 nm wavelength range with a spectral resolution varying between 1.5 to 5 nm (at full width at half maximum). The optical bench made of a carbon alloy is optimized to minimize the temperature dependence of the solar measurements to less than 0.1%K-1 for ambient temperatures ranging between -20°C to +40 °C. A Peltier temperature regulation system stabilizes the detector to better than 1 K while the overall structure is kept above a pre-defined temperature using a heating system to prevent cold temperatures. The PSR design benefits from the experience gained from successive generations of the successful Precision Filter Radiometers (PFR), which includes: an in-built solar pointing sensor, an ambient pressure sensor and several temperature sensors to provide routine quality control information which will allow autonomous operation at remote sites using an internal web-based server interface for instrument control and data retrieval.

The design of the PSR has now been finalized and a commercial version of the instrument has been constructed, with first units available since March 2014.

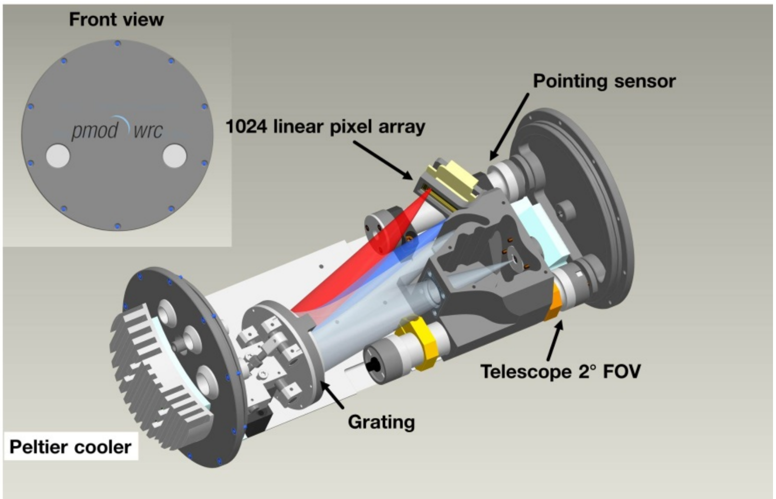

Figure 1. Schematic layout of the PMOD Precision Spectroradiometer.

24 Intercomparison of CCD Array and Scanning Spectroradiometers for Solar UV Measurements in Australia

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An intercomparison between three Public Health England (PHE) CCD array spectroradiometers and an ARPANSA (Australian Radiation Protection and Nuclear Safety Agency) double grating scanning spectroradiometer was carried out in Melbourne, Australia from 29 October to 7 November 2013. The three CCD array spectroradiometers used were a B&W Tek Glacier, an Ocean Optics QE65000 and an APSUS – a self-contained unit incorporating an Ocean Optics QE65000. All three CCD array spectroradiometers were thermoelectrically cooled. Solar UV spectral irradiance measurements – both erythemally weighted (UV Index) and unweighted – were compared. This was done with the CCD array spectroradiometers calibrated using the PHE calibration chain and then also with these spectroradiometers calibrated directly to the ARPANSA double grating scanning spectroradiometer. The results of this intercomparison are shown.

25 Up-conversion photonics in rare-earth doped materials for enhancing incoming UV solar irradiation

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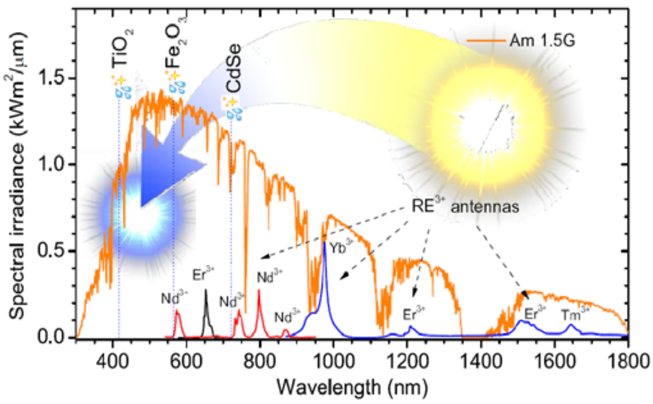
Up-conversion photonic processes convert photons from the near infrared range into the UV-visible through multi-photon and energy transfer mechanisms. In that sense rare-earth (RE) doped materials, presenting efficient up-conversion luminescence, appear as one of the most promising candidates to assist long wavelength light harvesting of solar irradiation, for different technological applications. In fact this up-conversion photonic approach has already been extensively developed to increase the efficiency in photovoltaic solar cells1 by the spectral shift of the sun's irradiation, and also to increase the production in agriculture by improving the sunlight conversion efficiency of the photosynthetic process. Moreover, these up-conversion luminescent materials, which transform the unused red and near-infrared sunlight tail into available UV-VIS radiation, extend the spectral response of semiconductor electrodes to enhance photocatalytic activity for solar sustainable production of hydrogen using a photo-electrochemical (PEC) water-splitting cell, for example. Transforming the incoming infrared into blue radiation provides extra photons for absorption by the large band-gap semi-conductor electrodes used in the water-splitting devices. In other words, it is not just a question about optimizing the PEC cell or the semiconductor catalysts; it is a question of optimizing the incident radiation, turning the sun into blue, for an endless range of technological possibilities. Here we present a suitable candidate towards this goal, by means of highly efficient UV-VIS up-conversion emissions2 in a RE co-doped (Yb-Er-Tm) fluoride glass (ZrF4– BaF2–LaF3–AlF3–NaF, ZBLAN) under near-infrared excitation at 980 nm, to enhance solar-driven activity of efficient commercial photocatalyst such as TiO2.



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