UV NEWS

The official newsletter of the Thematic Network for Ultraviolet Measurements

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Contents

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Helsinki University of Technology
Metrology Research Institute
Petri Kärhä
P. O. Box 3000
FIN-02015 HUT, Finland

Telefax: +358 - 9 - 451 2222
E-mail: petri.karha@hut.fi

In case of longer articles or announcements, use of E-mail is preferred. The date of the next possible issue is not known. It will most likely be published with the 6th workshop around 2004 – 2005.

Photographs: Cover, Participants of the 5th Workshop (Günther Seckmeyer) Page 3, View from the lecture hall (Peter Sperfeld).

The Fifth Workshop in Halkidiki, October 7 - 8, 2002

Petri Kärhä
Helsinki University of Technology, Finland

The fifth workshop of the Thematic Network for Ultraviolet Measurements was arranged in Halkidiki, Greece, on October 7-8, 2002. The meeting was hosted by the Aristotle University of Thessaloniki (AUTH). The number of participants in the workshop was 51.

The structure of the workshop was renewed from what we have had earlier. In preceding workshops lots of time has been allocated for working group meetings. In this workshop, this time was reserved for open discussions on themes selected to cover most of the work of the working groups.

The discussion on recent topics of interest in solar UV measurements was chaired by Günther Seckmeyer. Of the various topics discussed, one receiving most attention was the poor stability of transfer standard lamps that are used to transfer traceability from national standards laboratories to solar UV instruments. Various groups have noted that the FEL-lamps typically used as standards change during transportation even if the lamps are hand-carried. It was pointed out that the problem has already been solved by introducing detector stabilised lamps, where the output of the light source is continuously monitored with one or more wavelength selective photodiodes. However, these lamp types have never achieved commercial success.

Another concern was the poor agreement between the scales of different national standards laboratories. The accuracy of solar UV measurements has already reached a level, where variation between national standards laboratories is a major source of uncertainty. Emma Woolliams and Peter Sperfeld presented some improvements that have been carried out at NPL and PTB to improve the basic realisations. High-temperature black bodies with radiometric determination of the temperature should improve the measurement uncertainties to an acceptable level.

The discussion on recent topics of interest in medical UV measurements was chaired by Harry Moseley. One of the mainstream topics within the medical measurements seems to be the use of small hand-held array spectroradiometers for medical measurements. As a sub-presentation to the topic, Wolfgang Heering spoke about "Application of Compact Array Spectroradiometers for the Determination of Weighted UV Irradiance." Another presentation on the same subject field was given later by Hannah Oliver.

The author is with
Helsinki University of Technology
Metrology Research Institute
P.O.Box 3000
FIN-02015 HUT
Finland

E-mail: petri.karha@hut.fi

Array spectroradiometers seem to offer an attractive substitute to broadband UV meters. The measurement results can be weighted mathematically to produce any action spectrum desired for the meter. However, it seems that array spectroradiometers generate other problems that need to be solved. The main limitations are the stray light levels and the low sensitivities.

The discussion on calibration and intercomparison issues with broadband UV meters was chaired by Petri Kärhä. To begin the discussion, Anton Gugg-Helminger presented "Manufacturer's view on UV meters with different action spectra." In the earlier years of the Network, WG1 has done an extensive job on considering the methods for calibrating broadband UV meters. The presentations described results on meter calibrations carried out using the methods recommended in *UVNews* **6**. It may be concluded that in theory all problems related with UV meter calibration have been solved, but what about practice?

One conclusion of the discussion was that an intercomparison should be carried out. Intercomparisons typically show poor agreement because methods vary. Using the methods summarised in the extended abstracts of Gugg-Helminger and Kärhä (starting on pages 20 and 29), it should be possible to arrange a successful intercomparison. An intercomparison on UV meter calibrations piloted by HUT is planned for the near future. Those who would like to participate should contact Petri Kärhä.

The rest of the time was allocated for scientific presentations:

- Radiometric Methods for UV Process Design and Process Monitoring for Industrial UV Curing, R. W. Stowe
- Realisation and dissemination of spectral irradiance at NPL, Emma R Woolliams
- An Evaluation of two Diode Array Spectroradiometers for use in a Medical Context, Hannah Oliver
- Dosimeter Study of Pre-school Children's UV-exposure, Ulf Wester

Richard Stowe's presentation was on a subject field of UV curing of materials, a field that has not been discussed very much within the Network. It was very nice to have one of our American colleagues taking part in the workshop. This highlights the fact that the problems of UV measurements do not recognise the continents.

As the Borås workshop, also this workshop was closed by the presentation of Ulf Wester. At least for me, Ulf's presentation gave a reminder for why I do this UV work: I study UV to make the world a better place for the children to live.

In addition to the oral presentations, there was a poster session on Monday evening. The session had 9 posters covering various projects active within the UV measurements.

On Tuesday afternoon, there was an excursion to the Laboratory of Atmospheric Physics (LAP) of the Aristotle University of Thessaloniki (AUTh). The laboratory has a nice location on the roof of the university close to the measurement setups. Peter Sperfeld's photographs on the lab tour are available in the web-pages of the Network.

The local organisers at AUTh, especially Alkiviadis Bais, did an excellent job in arranging the workshop. On behalf of all participants, I would like to thank Alkis one more time!

Many authors used their opportunity to publish extended abstracts of their presentations. These extended abstracts are included in the following section.

Extended Abstracts

The Norwegian UV-monitoring program
Period 1995/96 to 2001

Bjørn Johnsen[1], Oddbjørn Mikkelborg[1], Arne Dahlback[2], Britt Ann Høiskar[3], Kåre Edvardsen[3], Jan Olseth[4], Berit Kjeldstad[5], and Jon Børre Ørbæk[6]

[1] *Norwegian Radiation Protection Authority, Østerås, Norway*
[2] *Dept. of Physics, University of Oslo, Norway*
[3] *Norwegian Insitute for Air Research, Kjeller, Norway*
[4] *Geophysical Institute, University of Bergen, Norway*
[5] *Norwegian University of Science and Technology, Department of Physics, Trondheim, Norway*
[6] *Norwegian Polar Insitute, Longyearbyen, Svalbard, Norway*

Highlights:

- UV-monitoring is performed at 8 locations between 58°N and 79°N.
- The experiences with the network implementation and operation are very good.
- Calibrations are traceable to several European UV networks, through the Nordic Intercomparison of UV and total ozone instruments in Sweden 2000.
- The measurements have been validated and found consistent.
- Six years of complete series of daily erythemally effective UV-doses and UV-indexes are available for public and scientific use.
- The measurements are relevant for the assessments of health- and environmental aspects of UV-radiation.
- The measurement series are yet too short to infer any trend in the UV-radiation.
- Measurements are presented on-line on http://uvnett.nrpa.no/
- UV-forecasts are provided by the Norwegian Institute for Air Research (NILU) on http://www.luftkvalitet.info/uv/

A Norwegian UV-monitoring network of GUV multiband radiometers has been operating at locations between 58°N to 79°N since 1995 – 96. The purpose is to obtain long-term series of UV data of high quality, to be used in further assessments related to health- and environmental issues. The Ministry of Health and The Ministry of Environment finance the network. The network is administered by The Norwegian Radiation Protection Authority (NRPA) and The Norwegian Pollution Control Authority (SFT), the latter through The Norwegian Institute for Air Research (NILU).

Six years of UV measurements are available. Calibrations of instruments are traceable to the Nordic intercomparison of UV radiometers held in Sweden in June 2000 (NOGIC2000). The change of calibration scale results in a step in daily UV-doses by about 10 % as compared to

The corresponding author is with
Norwegian Radiation Protection Authority
Section for non-ionising radiation
P.O.Box 55
N-1332 Østerås
Norway

E-mail: bjorn.johnsen@nrpa.no

the previously reported UV doses based on the manufacturer calibrations. The change implies improved accuracy for large solar zenith angles as well. The present annual report comprises a re-evaluation of measurements for the period 1995/1996 to 2001.

Maintenance of measurement quality and continuity in measurements is given priority. Daily or weekly inspections of instruments and online graphical display of UV measurements on the Internet (http://uvnett.nrpa.no/) provide early warning in case of instrument failure. Power backup systems have been installed at five stations to improve the continuity in measurements. Frequently occurring failures of detector controllers have been eliminated, following a modification scheme designed by NILU. Two complete GUV radiometers and four spare detector controllers have been purchases to serve as backup.

Once a year the instruments are calibrated to mobile transfer standard instruments. This enables determination of the long-term change in instrument responses for the purpose of maintaining a stable calibration scale over many years. For the six years period of operation, the best instrument performed stable within ±3 % for the five wavelength bands, whereas the oldest and least steady instrument had response drops up to 23 %.

The optical laboratory at NRPA enables accurate monitoring of response changes in the mobile transfer standard instruments, using a set of lamps dedicated for these instruments. Optical feedback regulated lamps as well as conventional current-stabilised lamps are used for this purpose. Annual calibration controls by the manufacturer enable an independent evaluation of one of these transfer standards. There is a good agreement between the manufacturer's and NRPA's results for lamp measurements.

Spectral response functions have been measured for all instruments. The response functions enable calculation of physically unweighted or biologically weighted UV irradiances from the raw data. Angular response functions have been measured for six instruments and cosine errors calculated for different sky conditions and solar zenith angles. This enables means for correcting systematic errors in raw data.

The characterisations and calibrations of the instruments are performed by NRPA, using our calibration facilities and reference instruments. A platform at the roof serves the purpose of solar calibration of network instruments, as well as providing a site for reference measurements. A Bentham DM150BC spectroradiometer, fitted with a close to ideal cosine receptor, provides highly accurate spectral measurements for the wavelength region 290 – 450 nm (optional 500 nm). Quality control of spectra follows recommendations from the World Meteorological Organization. Blindtest intercomparisons performed during the NOGIC2000 showed that the spectroradiometer agreed within -1 % ±2 % with the campaigns reference spectra for all solar zenith angles and days. The mobile transfer standard GUV instruments have been calibrated towards this spectroradiometer. Comparisons between these transfer standards and the spectroradiometer show close agreement in erythemally effective doserates (±2 %) for solar zenith angles less than 80°. Calibration of local network instruments is performed applying the transfer standards. The erythemally-effective doserate measured with the local network station GUVs match the transfer standards within ±1 % for solar zenith angles less than 80°. Daily UV doses recorded with the local GUV's and the transfer standard GUV agree within ±1 % for the 6 years of intercomparisons. Thus there is a highly consistent chain of calibration steps starting with the reference spectroradiometer participating in the NOGIC2000, the calibration of transfer standard GUVs toward this reference spectroradiometer, and finally the transfer from travelling standards to network instruments.

Failures with the GUV instrument's temperature-controllers and computers, power shutdowns, work related to calibrations and spectral characterisations of instruments etc. have resulted in several gaps in measurement series. The number of days with significant gaps in measurement data varies between 0 and 10 per year for most stations. However, the instrument in Tromsø that in year 2000 was moved to Andøya has had excessive gaps, with more than 70 days with significant gaps in 2000 and 2001. Estimates of the loss of annual UV doses that have been cumulated since 1996 amount to 5 % to 20 % for all stations, except for the Tromsø/Andøya stations where the loss is 63 %.

Gaps in integrated daily UV doses and maximum UV-indexes have been corrected by using total global irradiance measurements from nearby pyranometers to estimate the UV sky transmittance. With exception of Andøya, pyranometer data exist for all stations. For Andøya, UV sky transmittances have been assumed constant, or taken as an average of the period before and after the gap. Clear-sky UV-indexes were calculated with a radiative transfer model and modified according to the hourly mean UV sky transmittances. The agreement between estimated and measured daily UV doses is generally within ±15 % for variable cloud conditions. The method of retrieving UV doses from ancillary measurements significantly improves the accuracy of estimates of monthly and annual UV doses. The uncertainty in annual UV doses resulting from estimated gaps in measurement series is less than ±1.5 % for stations with pyranometers. For the Andøya station the gaps have affected the annual UV doses by up to ±6 %.

Time series that have been corrected for gaps indicate different interannual variations in total UV doses for the stations in southern and northern Norway. Stations from Trondheim and southwards show large variations (±12 %) in the period 1996 – 1998, followed by a fairly stable (±3 %) period in 1999 – 2001. For the same stations a maximum (12 %) were seen in 1997 and a minimum (-12 %) in 1998. Pyranometer data show that the UV sky transmittance was about 10 – 15 % higher during the summer months of 1997 than in 1998, indicating a more sunny summer. The total ozone amount was about 10 % lower in the summer months of 1997, resulting in higher clear sky UV doses. The combined enhancement and reduction of UV radiation from variations in cloud and ozone amount may explain the differences seen in 1997 and 1998.

For the two northern stations a minimum in annual UV doses were observed in 1999, however not as pronounced as in 1998 for the southern stations. Tromsø/Andøya had a maximum in annual UV doses in 1997, a summer renown for its long period of clear sky conditions, followed by a fairly stable (±3 %) period for the last 3 years. The annual UV doses for Ny-Ålesund were fairly the same (±1.5 %) in 1996-1998 and in 2001. The minimum (-12 %) in 1999 is largely affected by the overcast conditions of June and July. The short summer season implies that the annual UV doses will be most affected for the stations in the north.

The annual UV doses have been non-statistically significantly lower in the period 1999 – 2001 than in 1996 – 1997. The interannual variations are however too large and the observation period too short to infer any statistically significant trend in the UV-radiation.

All raw data and processed data for the GUV instruments, calibration and correction factors are stored in a SQL database developed at NRPA. The database provides a powerful tool for data storage and retrieval. The website http://uvnett.nrpa.no/ is linked to this database, which enables access to updated UV information to the public. Measurement data and information about the monitoring network are provided by NRPA, NILU and The University of Oslo at http://www.nrpa.no, http://www.luftkvalitet.info/uv/ or http://www.fys.uio.no/plasma/ozone/. Forecasts of UV-indexes for different regions of Norway are provided by NILU. The service is available on NILU’s web site since 2001.

Dosimetry in phototherapy

Laura Huurto[1], *Erna Snellman*[2], *and Lasse Ylianttila*[1]

[1] *STUK, Radiation and Nuclear Safety Authority, Finland*
[2] *Department of Dermatology, Central Hospital of Päijät-Häme, Finland*

Introduction

Artificial ultraviolet radiation (UVR) is used in phototherapy, the medical treatment of various skin diseases like psoriasis and atopic eczema. Both solar and artificial UVR exposure have also carcinogenic effects. Long term phototherapy with high cumulative UVR doses is shown to be risk for squamous cell carcinoma [1,2].

Various biological effects are strongly dependent of the wavelength of the UVR. UV-B-radiation with short wavelength (280 – 320 nm) is more effective to cause sunburn of the skin than UV-A -radiation with longer wavelength (320 – 400 nm). The correlation between wavelength of UVR and the tissue sensitivity is described by action spectra. An action spectrum is a mathematical model describing the efficiency of UVR of different wavelength for producing a certain biological phenomena [3]. Specific action spectra have been determined for the most important health effects like erythema and skin cancers [4,5].

Phototherapy devices

In most of phototherapy devices the UVR sources are fluorescent tubes. There is a wide selection of lamps producing different UVR spectra.

The corresponding author is with
STUK, Radiation and Nuclear Safety Authority
Non-Ionizing Radiation Laboratory
P.O.Box 14 (Laippatie 4)
FIN-00881 Helsinki
Finland

E-mail: laura.huurto@stuk.fi

Phototherapy devices are classified to three main categories by the UVR spectrum (Figure 1):

1. PUVA-devices are equipped with UV-A-lamps and they are used with certain photosensizing drugs, psoralens, for PUVA-treatments (PUVA = psoralen + UVA);
2. UV-B-devices are equipped with broadband or narrow band UVB-lamps;
3. SUP-devices. SUP is an abbreviation of Selective UV-phototherapy; SUP-spectrum lies between spectra of UV-A and UV-B-lamps, and it is commonly used for phototherapy in Nordic countries. In Germany SUP refers to treatments with UV-B-lamps.

Devices intended for whole body treatments are mostly cabins or cubicles where lamps are placed in vertical panels surrounding the patient. Sunbed shaped devices are also used. In local treatment of hands and feet a typicall phototherapy device is a small size panel installed in an adjustable stand.

Dosimetry

The concept of the “dose” in photobiology and in photomedicine differs significantly from the one in radiobiology. The UVR dose is defined as the radiant exposure on the surface (3). This concept does not take into account which proportion of the UVR is absorbed in the tissue and which is reflected or transmitted.

Traditionally phototherapy has based on assessment of the skin erythema between exposures. The redness of the skin has been used as an indication to shorten or lengthen the irradiation times. There has been no means to assess the treatment doses.

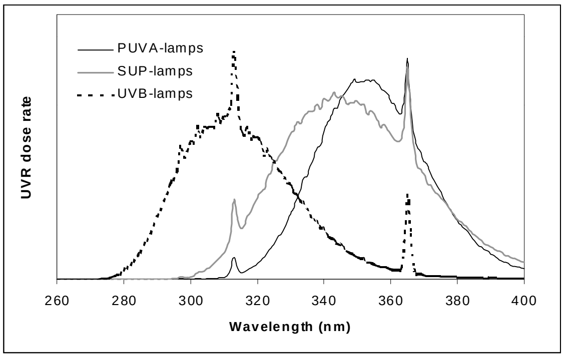

Figure 1. UVR spectra of three different kind of UV-lamps intended for medical purposes. The spectra are scaled to their maximum values.

The dose rate of phototherapy devices can be assessed by simple hand-held UVR-meters. When the dose rate is known, it is possible to determine the UVR dose delivered in each treatment exposure as well as the cumulative dose of a patient. In these cases treatment regimens can be planned and carried out by the means of UVR doses instead of exposure times. Nowadays some of the most advanced phototherapy devices have an intrinsic meter to monitor the intensity of UVR and an automatic system to adjust the length of the exposure time when the dose rate changes.

It is essential that the UVR-meter is calibrated against the spectrum of the measured UV-lamps [6,7]. An uncalibrated or inadequately calibrated meter may cause a gross error in the measurement result.

When the treatment regimens are based on the actual UVR doses it is possible to compare the results of exposure regimens in different clinics [8]. This allows to assess the efficiency of the treatment regimens and to optimise them.

The UVR dose rates of the phototherapy devices decrease when the lamps age. To maintain the intended treatment regimens the exposure times should be lengthened respectively to compensate for the lower dose rates. On the contrary, when aged lamps are replaced with fresh lamp sets, the dose rates are significantly higher. This may cause overexposure and skin burns if exposure times are not shortened appropriately.

Clinical practice in Finland

Although more than half of the phototherapy clinics in Finland have an UVR-meter they are seldom used for dosimetric purposes. In some cases regular dose rate measurements were carried out by service men only to monitor when it is time to replace a fresh lamp set but the measurement results were not utilised in the treatments. There is also a wide variation between the clinics in making the decision when it is time to replace the aged lamps by new ones. Only in few clinics treatment regimens are based on UVR doses, the majority still follows time-based regimens. Thus, the recording of each patient’s cumulative UVR doses has not come into practice [9].

Recommendations

Dermatologist in Britain and in U.S.A have given recommendations to keep records of the UVR doses of the patients [10,11]. Similar recommendations are also given in Finland by STUK and the National Agency of Medicine [7,12]. The main points of the Finnish recommendations are following [7]:

- The personnel should have sufficient training to operate phototherapy devices.
- Phototherapy devices should have written instructions for use.
- The dose rate should be monitored by a calibrated UVR meter.
- Records should be kept on matters affecting to the UVR doses of phototherapy devices, i.e., the type of the lamps and dose rate.

- UVR doses of each patient should be recorded and treatment doses should be kept as low as convenient for the treatment.
- Patients' eyes shall be protected always and also critical skin areas should be covered if convenient.
- A regular review of patients with high UVR doses is recommended to detect malignant skin lesions.

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Application of compact array spectroradiometers for the determination of weighted UV irradiance

Wolfgang Heering
LTI, University of Karlsruhe, Germany

Today a variety of UV sensors are available, mostly broad-band radiometers, i.e. usually photodiodes behind a diffuser and a filter within a certain aperture. They are used to control or to monitor an UV process, i.e., photochemical reactions in materials or UV hazards presented to the human skin or eye. This is why actinic radiant quantities rather than physical quantities are to be measured. However, matching of the relative spectral response of an integrally measuring radiometer to the action spectrum under consideration is mostly not perfect, especially, if different radiation sources are to be assessed by the same radiometer. Moreover, one radiation source can produce more than one actinic effect so that several broadband radiometers or heads are necessary at the working place.

So for UV processing, more and more spectroradiometers are inserted instead of filter radiometers. This became possible by the development of very compact spectroradiometers, so-called mini- or microspectrometers which can easily be integrated into the process equipment. They are manufactured with outer dimensions of down to 20 x 30 x 4 mm, provide long term stability and industrial ruggedness and can be digitally controlled, read-out and programmed to give defined actinic irradiances.

The optical design of such a minispectrometer is typically either a Czerny-Turner arrangement with a plane reflection grating, a collimating mirror and a focusing mirror or a Rowland mount with a self-focusing blazed concave reflection grating of flat-field type. Figure 1 shows the optical arrangement we have developed to measure absolute spectral irradiances from 200 nm to 800 nm [1]. The background signal has been strongly reduced by Peltier cooling of the array and dark signal subtraction.

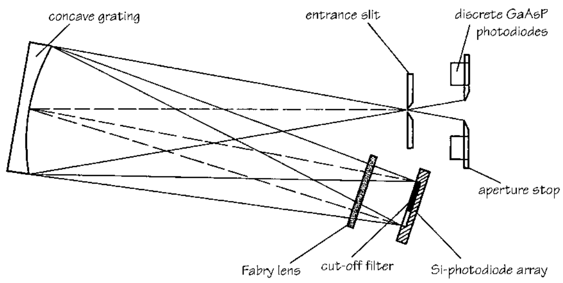

Figure 1. Array-spectroradiometer for the UV and VIS with Fabry lens increasing the effective height of the photodiode array, with cut-off filter on the array to suppress higher order and front GaAsP diodes for absolute integral measurement of irradiance.

By means of the LIGA technology the optical components as grating, plate-type waveguide, entrance slit and output mirror can be precisely microstructured to a flat compact monolithic device with a rather high optical throughput (Fig. 2). This technique has been successfully applied for use in the VIS and NIR and can be extended to measure the UV by using the second order of diffraction. Radiation is usually coupled into such microspectrometers via a fibre. The dispersed radiation components are simultaneously detected by a linear array of photodiodes or CCDs.

The author is with
Universität Karlsruhe
Lichttechnisches Institut
Kaiserstrasse 12
DE-76131 Karlsruhe
Germany

E-mail: wolfgang.heering@etec.uni-karlsruhe.de

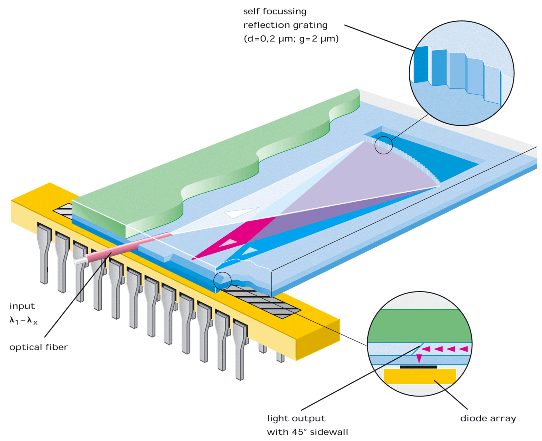

Figure 2. Monolithic flat array spectrometer device fabricated by means of LIGA technique [2].

The main highlights of such compact spectroradiometers are ruggedness because of no movable parts, sizes down to the range of some cubic centimetres, programmable wavelength range and weighting curve, digital control and low power consumption. Trade-off is often a poor spectral resolution in the order of several nanometers, limited dynamic range and, above all, the rather high stray-light level. As it was shown by A. Last [3], most of the false light is produced in LIGA spectrometers by periodic or non-periodic deviations of the position of the grating teeth; this can be reduced by a more exact LIGA masking technique. Generally false light can be limited by prefiltering at the entrance of the array spectroradiometer, aperture stops inside and outside of the radiometer, dichroic input and output mirrors, by a scanning predisperser as we have practised and by software correction. However in the UV, transmissive pre-filtering cuts off the spectral responsivity at the shorter wavelengths.

With respect to the uncertainties involved in the measurement with minispectro-radiometers, assessing of UV hazards as for instance the UV erythema generally requires a sharper spectral discrimination than it is necessary for the measurement of actinic irradiances which effect curing, photolysis, degerming and degradation of pollutions.

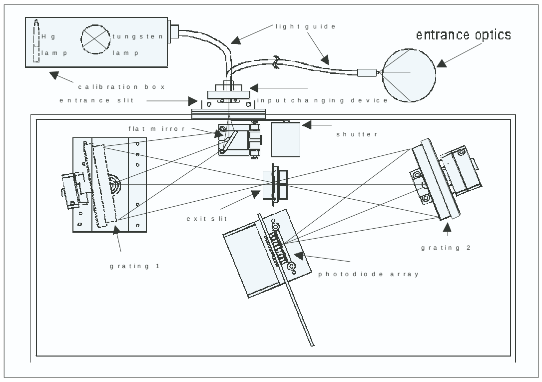

Figure 3. Modified Seya-Namioka mount: first stage as a tunable predisperser with a concave grating moved by a piezotranslator, second one a polychromator with RETICON TL256TBQ photodiode array.

In order to monitor solar UV trends we have developed a new kind of array spectroradiometer [4]. The modified Seya-Namioka arrangement (Fig. 3) includes two stages, i.e. a predisperser with a first holographic concave grating which is rapidly tuned step by step by means of a piezotranslator and a polychromator with six-fold higher linear dispersion and with a photodiode array in the focal plane of the second holographic focusing grating. Predispersion generates 3.6 nm wide spectra which are further dispersed in the second stage and simultaneously detected by some 18 photodiodes of the RETICON TL256TBQ array. 15 partial spectra are so taken one after the other, each with spectral bandwidth of 0.55 nm but with different exposure times and are then composed to a spectrum from 290 nm to 344 nm. By this method, a high dynamic range of up to 10^5 for a total measuring time of 1.5 sec and and a large stray light reduction by a factor $> 10^7$ are achieved.

Table 1. Comparison of some minispectrometers. The noise equivalent spectral irradiance is estimated from specifications of the manufacturer.

Array spectroradiometer type	Wavelength range /nm	Bandwidth (FWHM) / nm	Spectral pixel distance / nm	Noise equivalent spectral irradiance / nW $cm^{-2}nm^{-1}$	Stray light rejection
Sola-Sensor 2000	235 - 470	1	0.5	10	$> 10^3$
concave dichroic mirror + plane grating with diode array, 118 x 69 x 32 mm					
Self-made diode array spectroradiometer with predisperser (LTI)	290 – 344	0.55	0.2	3.2 (τ = 10 s)	$> 10^7$
2 x 210 mm focal length					
Specbos 1000 UV (JETI)	250 - 500	6	2	24 ($\tau = 10^{-2}$ s, λ = 400 nm)	$> 10^3$
flat field imaging holographic grating with diode array, 120 x 58 x 34 mm					
MMS UV (ZEISS)	200 - 400	3	0.8	10 (τ = 0.2 s)	> 333
Concave grating with diode array					
70 x 60 x 40 mm					
MAS 40 / UV (INSTR. SYSTEMS) with CCD array	200 - 600	2.5	0.2	5 (τ = 1 s)	$> 10^3$
145 x 90 x 185 mm					
UV/VIS-LIGA-Micro-spectrometer (MicroParts)	320 – 920 in 1st order	< 10 nm	3.5		$> 10^3$
with Si-detector array	220 – 350	< 5 nm	1.75		$> 10^3$
54 x 32 x 35 mm	in 2nd order				

Table 1 presents a comparison of some minispectrometers. Obviously not the spectral resolution and the spectral range are problems with such instruments when measuring effective irradiances. However, the quite high stray light level and the detection limit given by the noise equivalent spectral irradiance make it difficult to measure weak but effective spectral irradiances together with strong, but less effective spectral irradiances. As our measurements have shown, the erythemal irradiances produced by broad-band radiation sources, as for instance by Xenon short arcs, are strongly overassessed by array spectroradiometers due to the large false light contribution in the shorter UV. However the erythemal irradiance of sun lamps with a much smaller spectrum are assessed with much smaller uncertainties as A.W. Ridyard has experienced when using a Solatell array spectroradiometer [5].

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A portable field calibrator for solar ultraviolet measurements

Lasse Ylianttila[1], *Petri Kärhä*[2], *Kari Jokela*[1], *and Erkki Ikonen*[2]

[1] *STUK, Radiation and Nuclear Safety Authority, Helsinki, Finland*
[2] *Helsinki University of Technology, Finland*

Introduction

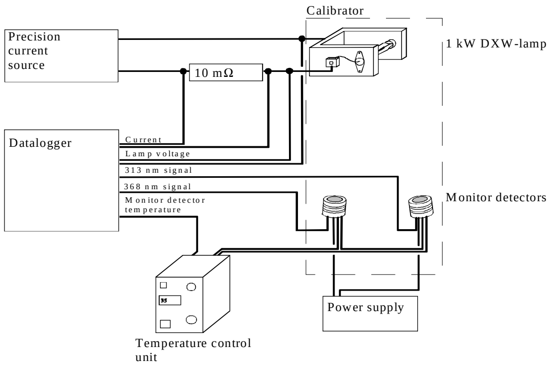
Stationary roof-mounted spectroradiometers are used to monitor changes in the solar UV radiation passing through the atmosphere. We have developed a portable detector-monitored calibration system,[1] which can be used to calibrate the spectroradiometers on the measurement site thus reducing the need for transportation of the spectroradiometer.

Description of the calibrator

The calibrator utilises a 1-kW DXW lamp as the light source (Figure 1). The output of the light source is continuously monitored with two temperature-controlled filter radiometers at 313-nm and 368-nm wavelengths. The lamp is operated in current-stabilised mode. When the ageing characteristics of the lamp are known, the signals of the monitoring filter radiometers can be used to calculate corrections for the spectrum as the lamp ages. The alignment and distance adjustment is done by instrument-specific adapter plates.

Ageing of DXW-lamps

To study the ageing properties of DXW-lamps two pre-aged 1-kW lamps were burned for over 80 hours simulating the normal use of the lamps.[2] The irradiance measured by a spectroradiometer decreased about 4 % in 80 hours (Figure 2).



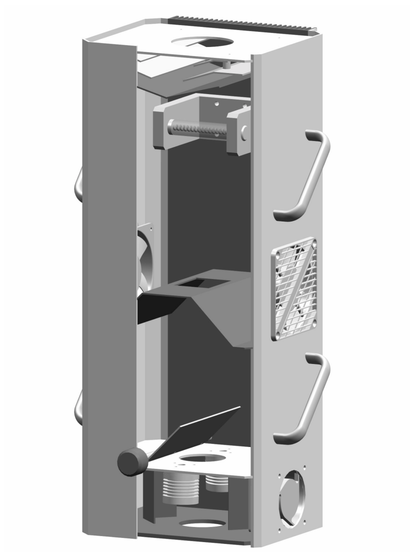


Figure 1. Schematic diagram of electronics and the interior of the calibrator.

The difference between the lower and the higher wavelengths was 1%. The spectral changes can be fully explained by changes of the filament temperatures, which decreased about 8 K during the 80-h burns.

The corresponding author is with
STUK, Radiation and Nuclear Safety Authority
Non-Ionizing Radiation Laboratory
P.O.Box 14 (Laippatie 4)
FIN-00881 Helsinki
Finland

E-mail: lasse.ylianttila@stuk.fi

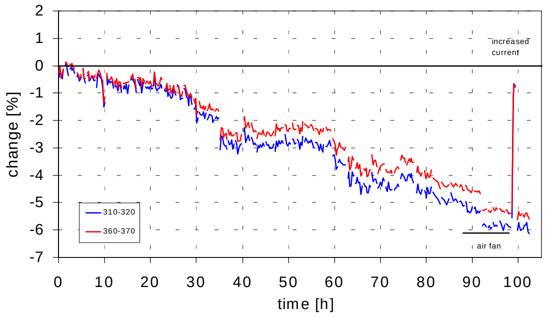


Figure 2. Measured changes of different 10-nm bands during the test-burn of DXW-lamp.

Testing of the calibrator

The calibrator has been thoroughly tested in both laboratory and in field. The stability of the monitor-detectors are presented in Figure 3. The results of the field calibrations indicate that the device works satisfactorily under a wide variety of environmental conditions. The device can be used in summer, when temperature can be as high as 30°C and direct sunshine heats the housing of the calibrator.

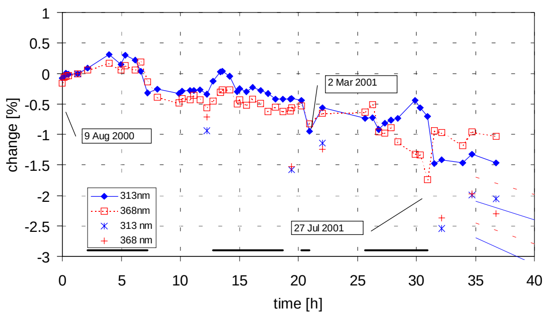


Figure 3. Stability of the calibrator. The lines represent the signals measured by the monitor detectors and crosses represent measurements by the spectroradiometer.

Successful calibrations have also been carried out in winter, with mild snow and ambient temperature of -7°C (Figure 4).

The spectral irradiance in the output of the calibrator is calibrated either with a spectroradiometer or absolutely characterised filter radiometers. The use of latter provides the shortest possible traceability chain for the calibrations.

Figure 4. Test-measurement was made at Jokioinen observatory in winter 2001.

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1. P. Kärhä, L. Ylianttila, T. Koskela, K. Jokela, and E. Ikonen, "A portable field calibrator for solar ultraviolet measurements," *Metrologia* (accepted).

2. L. Ylianttila, K. Jokela, and P. Kärhä, "Ageing of DXW-lamps," *Metrologia* (accepted).

Acknowledgements. The work has been carried out within project SMT4-CT98-2242 "Improving the Accuracy of Ultraviolet Radiation Measurement", funded by the Standards, Measurements and Testing program of the European Union. The authors thank Asko Turunen for building the mechanics of the calibrator and Toomas Kübarsepp for building the monitor detectors.

High-intensity setup for measuring spectral irradiance responsivities of UV meters

J. Envall, P. Kärhä, and E. Ikonen
Metrology Research Institute, Helsinki University of Technology, Finland

Introduction

Measurement of the spectral irradiance responsivity of UV meters is often complicated because of the limited resolution of the meters. HUT has started a project to develop a high-intensity spectral comparator facility. Equipment consists of a single grating monochromator and a light source. The equipment will be controlled with a computer and fully automised. The desired level of uncertainty for the calibrations is ~3 %.

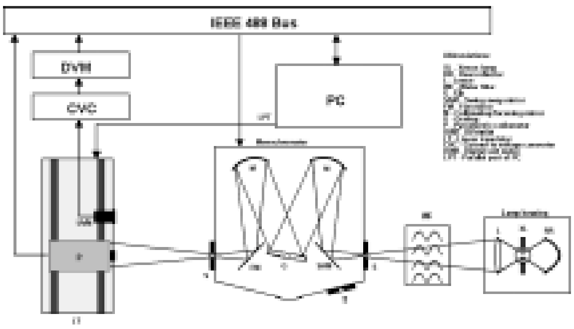


Figure 1. Schematic picture of the measurement setup.

Measurement setup

Figures 1 and 2 show a schematic picture and a photograph of the measurement setup.

450-W Xe, Hg and HgXe lamps will be studied as light sources. By selecting the Hg-lines, very high intensities may be obtained for calibration of meters used e.g. in lithography processes. Xe-lamps have a smooth continuous spectrum in the UV region that allows full spectral calibrations.

The monochromator used in the setup has two gratings optimised for UV and VIS. The monochromator can be operated over the spectral region 200 – 1200 nm.

Widths of the slits are adjustable so that the bandwidth of the output beam can be set within 0.5 – 10 nm.

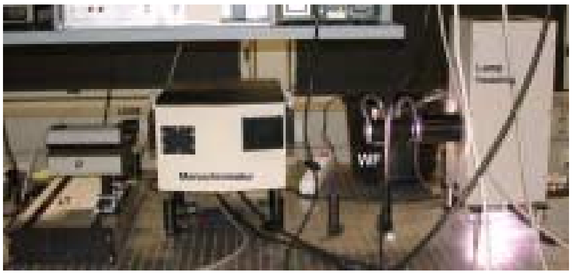


Figure 2. Photograph of the setup. Abbreviations as in Figure 1.

Characterisation scheme

The following measurements will be carried out in order to characterise the setup:

- Slit function of the monochromator is to be measured with several bandwidths and wavelengths, using the spectral peaks of a mercury pencil lamp.
- The data of the slit function measurements are used to calibrate the wavelength scale.
- The geometrical properties of the output beam - width, height, uniformity and *f*-number - will be measured.
- The irradiance level available for the calibrations will be measured.

The authors are with
Helsinki University of Technology
Metrology Research Institute
P.O.Box 3000
FIN-02015 HUT
Finland

E-mail: jenvall@cc.hut.fi

Preliminary measurements

The preliminary measurements have been carried out by using a Xe-lamp.

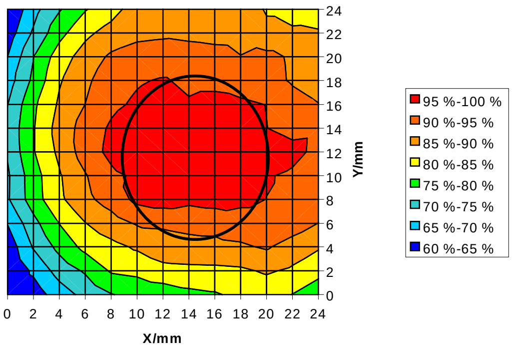


Figure 3. Spatial uniformity of the uncollimated output beam of the monochromator measured at 300 nm wavelength at a distance of 570 mm from the output slit.

Figure 3 shows an example of the uniformity of the output beam of the monochromator.

The irradiance level in the calibrations was measured to be 10 – 40 μW·cm^{-2}·nm^{-1} within the spectral region 250 – 400 nm, measured at 40 mm distance from the output slit. At 400 mm distance the irradiance level was 2 – 10 μW·cm^{-2}·nm^{-1}.

The slit function measurement was done with eight wavelengths, and these data were used to calculate a fifth-order correction polynomial for the wavelength scale.

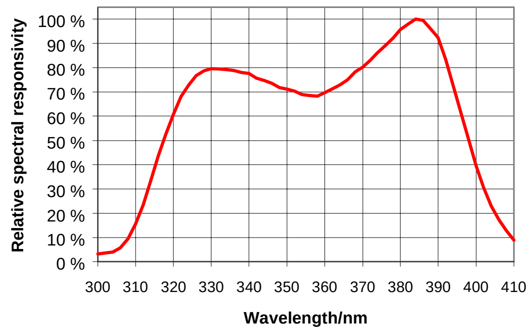


Figure 4. Relative spectral responsivity of a test UVA meter.

Test calibration

Figure 4 shows the result of the first test calibration carried out with the setup. The calibration has been performed using a calibrated apertured photodiode as the reference to reduce noise introduced in the measurements, if measuring directly against pyroelectric radiometer.

Manufacturer's view on UV meters with different action spectra

Toni Gugg-Helminger, Wolfgang Dähn, and Stephan Fenk
Gigahertz-Optik GmbH, Puchheim-Munich, Germany

When customers buy ultraviolet (UV) meters they have various expectations for the meters. One of the most fundamental expectations is that the new meter should give the same results as the meters of other manufacturers give. All too often this is not the case. One might question, is this possible at all? It is only possible, if the UV-detectors measure real values of the UV-source with a given action spectra.

To get equal results with two different UV meters, two items must be the same:

1. The spectral sensitivities of the detectors have to be equal, and

2. The calibration methods for the detectors have to be equal.

In general, both items are never equal. Therefore it is only possible to measure comparable values, if some information is given together with the UV-detector. This information should include at least:

1. The spectral responsivity of the detector,

2. Calibration method used, including the source(s) that have been used in the calibration.

If the spectral responsivity is given in graphical form, it should be given using both linear and logarithmic scales. This is demonstrated in Figure 1.

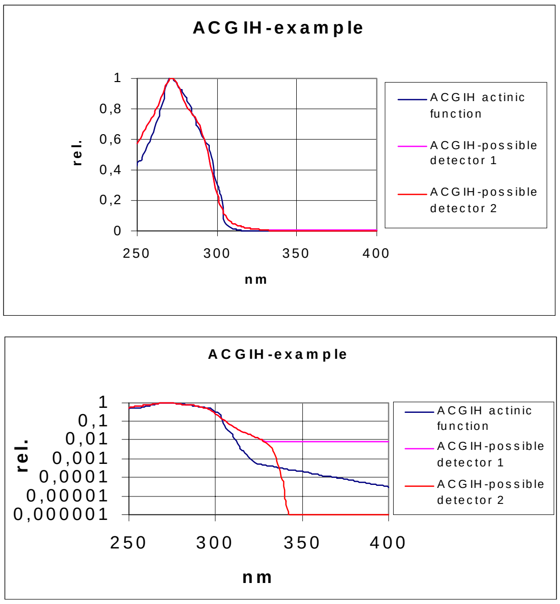


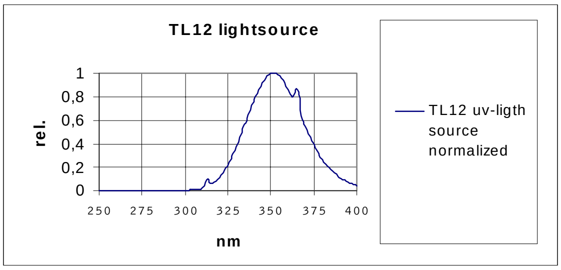
Figure 1. Spectral responsivities of two UV-meters with an ACGIH actinic response plotted on linear scale (above) and logarithmic scale (below).

The spectral responsivities of both ACGIH-meters seem very good and similar in the linear scale. However, the logarithmic scale reveals that there is a significant difference with the two specimens in the UVA region.

Let us demonstrate the effect of the "small" difference in the spectral responsivities. Figure 2 presents a spectrum of a TL12 light source, a typical measurement artefact for ACGIH-meters. We can calculate integrals of the weighted spectra to demonstrate the signals that we would obtain using an ideal ACGIH detector and the two physical detectors. The calculated integrals are presented in Table 1.

The authors are with
Gigahertz-Optik GmbH
Fischerstraße 4
DE-82178 Puchheim
Germany

E-mail: a.gugg-helminger@gigahertz-optik.com



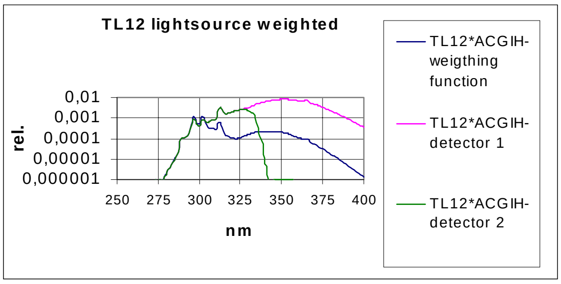


Figure 2. Relative spectral irradiance of a TL12 light source (above) and the same spectrum weighted with ACGIH action spectrum and the responsivities of the two ACGIH detectors (below).

The "small" deviation clearly requires a correction to be determined with proper calibration. The worst case for the correction factor is 17! With the other detector the correction factor is six times lower.

Table 1. Calculated signals of the two ACGIH meters and comparison to ideal values.

Response	Integral	Ratio to ideal
Ideal	0.0217	1.00
Detector 1	0.3750	17.25
Detector 2	0.0644	2.96

This example clearly demonstrates the need of getting accurate information on the spectral responsivity of the purchased meter from the manufacturer. Getting only linear or logarithmic plots may not give full information needed. A plot of "typical" responsivity curve does not take into account variations in the components of the meters, which in the above case resulted in a large change in the weighted responses.

Calibration factors for all UV-meters depend to a large extent on the source used for the calibration. Correction factors may be transformed from one light source to another using the *a*(*Z*) factors defined in [1]. The definition of *a*(*Z*) is

$$a(Z) = \frac{\int_0^\infty S_{\lambda,c} \cdot s(\lambda)_{act,rel} \cdot d\lambda}{\int_0^\infty S_{\lambda,c} \cdot s(\lambda)_{rel} \cdot d\lambda} \cdot \frac{\int_0^\infty S_{\lambda,Z} \cdot s(\lambda)_{rel} \cdot d\lambda}{\int_0^\infty S_{\lambda,Z} \cdot s(\lambda)_{act,rel} \cdot d\lambda}, \quad (1)$$

where $S_{\lambda,c}$ is the spectral distribution of the source used for calibration, $S_{\lambda,Z}$ is the spectral distribution of the source in a particular application, $s(\lambda)_{act,rel}$ is the (ideal) relative spectral actinic weighting function of the meter and $s(\lambda)_{rel}$ is the relative spectral responsivity of the radiometer head.

a(*Z*) values can be used as correction factors for various light sources. Use of the method requires knowledge of the spectra of the calibration source and the source to be measured, and relative spectral responsivity of the meter. An $a(Z) > 1$ indicates that the meter measures too low values, and $a(Z) < 1$ too high values without correction [Appendix].

The relative spectral responsivity can be measured or it can be taken from specifications of the manufacturer. To obtain highest accuracy, the spectra of the light sources should be measured as well. If extremely high accuracy is not needed, then the values can be taken from literature. Reference [1] lists spectra of various light sources used in ultraviolet work. These spectra are depicted in Figure 3.

To demonstrate the importance of considering the light source in calibrations, we have calculated *a*(*Z*) values for one of the ACGIH meters using the spectra depicted in Figure 3. The results are given in Table 2.

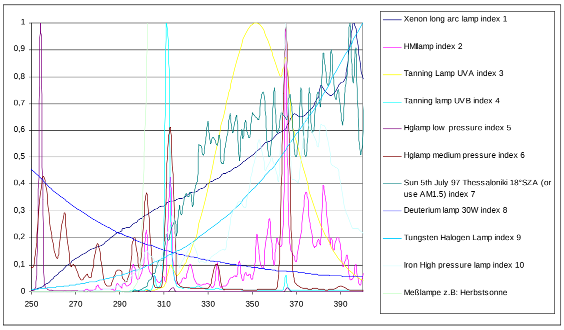


Figure 3. Typical spectra of UV light sources [1].

As can be seen, the calibration of the meter (level adjustment) has been carried out using an HMI-lamp. Measurement of any other light source requires use of a correction factor.

Table 2. a(z) values for an ACGIH meter to measure various light sources.

Source	***a*(*Z*)**
Xenon long arc lamp	0.992
HMI-lamp	1.000
Tanning Lamp UVA	6.311
Tanning lamp UVB	2.347
Hg-lamp low pressure	1.224
Hg-lamp medium pressure	0.896
Sun 5th July 97 Thessaloniki 18°SZA (or use AM1.5)	4.076
Deuterium lamp 30W	0.683
Tungsten Halogen Lamp	1.033
Iron High pressure lamp	1.111

Conclusions

There are various ways to build UV-meters for specific action spectra. The resulting meters have large variations in their spectral responsivities. Even within the same manufacturer, the tolerances in the optical components cause significant variations in the properties of meters. Therefore, the manufacturer should measure the spectral responsivities of all produced meters and give full spectral information on the meter to the customer. If the data is given in graphical form, both linear and logarithmic plots should be included.

All UV-meters require a correction factor, *a*(*Z*), if any other source than the source used for calibration needs to be measured. UV-sources vary to a large extent. Some sources emit only narrow peaks whereas other sources have continuous broadband spectrum. It is not possible to perform a common calibration that would be applicable to any light source.

Comparison of the measurement results of meters from different manufacturers requires knowledge on the spectral responsivities of the meters and the calibration methods used. It is possible to compare different meters, but not directly. A direct comparison gives different results due to different calibration methods used.

References

1. Working Group 1 of the Thematic Network for Ultraviolet Measurements, “Characterizing the performance of integral measuring UV-meters,” *UVNews* **6**, pages A-1 – A-26 and AA-1 – AA-36 (2000).

Appendix: The aspect of two different correct methods of calibration will give two different readouts

Toni Gugg-Helminger[1], *Wolfgang Dähn*[1], *Stephan Fenk*[1], *and Petri Kärhä*[2]

[1] *Gigahertz-Optik GmbH, Puchheim-Munich, Germany*
[2] *Helsinki University of Technology, Finland*

Spectral correction factor

For a spectral evaluation using the relative spectral responsivity data of a radiometer, which differ in certain spectral ranges from the prescribed weighting function, wrong measurement results may be obtained. When the responsivity is spectrally integrated, such differences may compensate each other. Comparing two relative spectral distributions, e.g. source *Z* and the calibration source *c*, possible deviations may compensate each other this way.

The ratio of the radiometric responsivity of the radiometer head irradiated by the source *Z* to the radiometric responsivity of the same radiometer head irradiated by the calibration source *c* leads to the relative responsivity *a*(*Z*) as defined in Eq. (1) in the article above.

If measurement of a source *Z* is carried out with the radiometer, previously calibrated with the calibration source *c*, the reading can be corrected according to

$$Y = \frac{Y_Z}{a(Z\ )}, \qquad (2)$$

where *Y* is the correct value, Y_Z is the reading of the radiometer when measuring the source *Z*, *a*(*Z*) is the relative responsivity according to Eq. (1). The reciprocal of *a*(*Z*) is also known as spectral correction factor.

The corresponding author is with
Gigahertz-Optik GmbH
Fischerstraße 4
DE-82178 Puchheim
Germany

E-mail: a.gugg-helminger@gigahertz-optik.com

Simplified calculation model and definitions

To understand above, some explanations:

From Eq. (2) it is shown, that an *a*(*Z*) > 1 gives a lower real value and *a*(*Z*) < 1 a higher real value.

Mathematically not quite correct, but we will simplify Eq. (1) to

$$a(Z) = \frac{S \cdot W}{S \cdot R} \cdot \frac{L \cdot R}{L \cdot W}, \qquad (3)$$

where *S* (source) = $S_{\lambda,c}$ is the spectral distribution of the source used for calibration, *L* (Lamp) = $S_{\lambda,Z}$ is the spectral distribution of the source in a particular application, *W* (weighting function) = $s(\lambda)_{act,rel}$ is the relative spectral actinic weighting function, and *R* (Radiometer) = $s(\lambda)_{rel}$ is the relative spectral responsivity of the radiometer head.

With this simplified model, we will vary *S*, *L*, *W*, and *R* to demonstrate effects that different shapes of these properties have on measurement results obtained with broadband UV meters. To make it easy we only use 3 different theoretical shapes – line function, radiometric broadband function, and triangular function. These functions are defined in Table 1 and presented in graphical form in Figure 1.

Table 1. Theoretical values at only 5 wavelength to understand the easy calculation.

wavelength nm	Line function	Broadband function	trialgular function
200	0	1	0
250	0	1	0,5
300	1	1	1
350	0	1	0,5
400	0	1	0

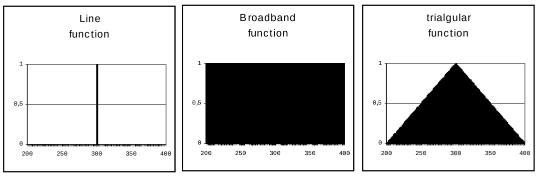


Figure 1. Theoretical shapes of 3 different possible spectral distributions valid for sources and detectors.

As seen from Eq. (3), we have to multiply all these functions, each with each other, wavelength by wavelength. Then we will get 6 different possible spectral distributions. The results of multiplication are shown in Table 2 and in graphical form in Figure 2.

Table 2. Results of the spectral multiplication.

wavelength nm	line function * Broadband function	triangular function * Broadband function	line function * triangular function	broadband function * Broadband function	triangular function * triangular function	line function * line function
200	0	0	0	1	0	0
250	0	0,5	0	1	0,25	0
300	1	1	1	1	1	1
350	0	0,5	0	1	0,25	0
400	0	0	0	1	0	0

As we can see, from the above calculation, when multiply by the broadband function (rectangular function) the result will be the same as the source. N.B: This is one of the reasons to try to get rectangular sensitivity of physical radiometric detectors (flat responsivity) – it does not change the information of a source.

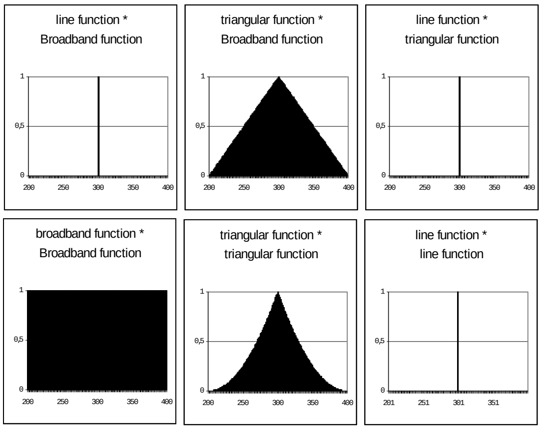


Figure 2. Spectral multiplication. The multiplied functions are defined in figures.

If we multiply a line function always a line function will be the result. If we multiply with a different function between the line up to broadband function, we will get all different shapes that are possible between line and broadband function.

Calculation examples

With the definitions given in the above chapter, we will do 4 examples.

Example 1

Consider spectral functions defined in Figure 3. Using the definitions given, we get the results presented in Table 3.

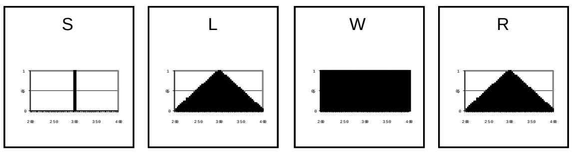


Figure 3. Functions for Example 1: Line function as a source, triangular function as a lamp, broad band function as weighting function, triangular function as radiometric head.

Table 3. Results of calculations for Example 1.

example1	Line function	Broadband function	result
wavelength nm	S	W	S*W
200	0	1	0
250	0	1	0
300	1	1	1
350	0	1	0
400	0	1	0
		Integral = Sum	1

example1	trialgular function	trialgular function	result
wavelength nm	L	R	L*R
200	0	0	0
250	0,5	0,5	0,25
300	1	1	1
350	0,5	0,5	0,25
400	0	0	0
		Integral = Sum	1,5

example1	Line function	trialgular function	result
wavelength nm	S	R	S*R
200	0	0	0
250	0	0,5	0
300	1	1	1
350	0	0,5	0
400	0	0	0
		Integral = Sum	1

example1	trialgular function	Broadband function	result
wavelength nm	L	W	L*W
200	0	1	0
250	0,5	1	0,5
300	1	1	1
350	0,5	1	0,5
400	0	1	0
		Integral = Sum	2

The results can be used to calculate $a(Z)$ with using the integral sum of each part:

$$a(Z) = 1/1 * 1.5/2 = 0.75$$

This figure informs us that the real value is too low. When we get a detector calibrated from a calibration laboratory with a line source, we will measure a value of 25% too low. The real value will be 1 instead of 0.75, but we do not know it.

Example 2

In this example we will vary only the source (Figure 4). Instead of a line source we will use a broadband source. All other parts are equal to Example 1. This means that we will change only the calibration method from line source to broad band source.

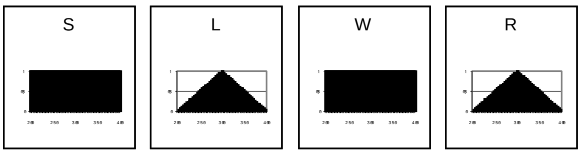


Figure 4. Functions for Example 2: Broadband function as a source, triangular function as a lamp, broad band function as weighting function, triangular function as radiometric head.

Table 4. Results of calculations for Example 2.

example2	Broadband function	Broadband function	result
wavelength nm	S	W	S*W
200	1	1	1
250	1	1	1
300	1	1	1
350	1	1	1
400	1	1	1
		Integral = Sum	5

example2	trialgular function	trialgular function	result
wavelength nm	L	R	L*R
200	0	0	0
250	0,5	0,5	0,25
300	1	1	1
350	0,5	0,5	0,25
400	0	0	0
		Integral = Sum	1,5

example2	Broadband function	trialgular function	result
wavelength nm	S	R	S*R
200	1	0	0
250	1	0,5	0,5
300	1	1	1
350	1	0,5	0,5
400	1	0	0
		Integral = Sum	2

example2	trialgular function	Broadband function	result
wavelength nm	L	W	L*W
200	0	1	0
250	0,5	1	0,5
300	1	1	1
350	0,5	1	0,5
400	0	1	0
		Integral = Sum	2

Calculating $a(Z)$ same way as with Example 1, we get

$a(Z) = 5/2 * 1.5/2 = 1.875$ > real value is too high.

This information will inform us that the real value is too high. When we get a detector calibrated from a calibration laboratory with a line source, we will measure a value of 87% too high. The real value will be 1 instead of 1.87, but we do not know it.

But be aware not to think always it is the same as shown above.

Example 3

Now we will use a line function instead of a broadband function as actinic function. You will see that the result is in opposite direction! In Example 3 we use as the calibration source a line function (Figure 5). The integrals to be used for calculating $a(Z)$ are calculated in Table 5.

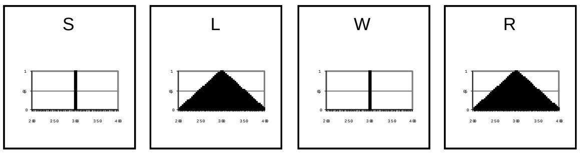


Figure 5. Functions for Example 3: Line function as a source, triangular function as a lamp, line function as weighting function, triangular function as radiometric head.

Table 5. Results of calculations for Example 3.

example3	Line function	Line function	result
wavelength nm	S	W	S*W
200	0	0	0
250	0	0	0
300	1	1	1
350	0	0	0
400	0	0	0
		Integral = Sum	1

example3	trialgular function	trialgular function	result
wavelength nm	L	R	L*R
200	0	0	0
250	0,5	0,5	0,25
300	1	1	1
350	0,5	0,5	0,25
400	0	0	0
		Integral = Sum	1,5

example3	Line function	trialgular function	result
wavelength nm	S	R	S*R
200	0	0	0
250	0	0,5	0
300	1	1	1
350	0	0,5	0
400	0	0	0
		Integral = Sum	1

example3	trialgular function	Line function	result
wavelength nm	L	W	L*W
200	0	0	0
250	0,5	0	0
300	1	1	1
350	0,5	0	0
400	0	0	0
		Integral = Sum	1

Calculation of $a(Z)$ gives us

$a(Z)$ = 1/1 * 1.5/1 = 1.5 > real value is too high.

Example 4

In example 4 we use as the calibration source a broadband function instead of a line function in Example 3.

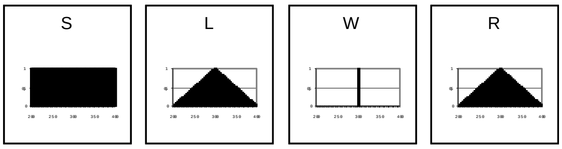


Figure 6. Functions for Example 4: Broadband function as a source, triangular function as a lamp, line function as weighting function, triangular function as radiometric head.

Table 6. Results of calculations for Example 4.

example4	Broadband function	Line function	result
wavelength nm	S	W	S*W
200	1	0	0
250	1	0	0
300	1	1	1
350	1	0	0
400	1	0	0
		Integral = Sum	1

example4	trialgular function	trialgular function	result
wavelength nm	L	R	L*R
200	0	0	0
250	0,5	0,5	0,25
300	1	1	1
350	0,5	0,5	0,25
400	0	0	0
		Integral = Sum	1,5

example4	Broadband function	trialgular function	result
wavelength nm	S	R	S*R
200	1	0	0
250	1	0,5	0,5
300	1	1	1
350	1	0,5	0,5
400	1	0	0
		Integral = Sum	2

example4	trialgular function	Line function	result
wavelength nm	L	W	L*W
200	0	0	0
250	0,5	0	0
300	1	1	1
350	0,5	0	0
400	0	0	0
		Integral = Sum	1

Calculation of $a(Z)$ yields

$a(Z)$ = 1/2 * 1.5/1 = 0.75 > real value is too low.

Summary and conclusions

From above we could see, that it is no general information for the readout value depending on peak (often line) or broadband calibration. Also an estimated result depending on the shape of the detector is not always valid.

For a good rectangular radiometric detector we expect the real answer of a lamp. The integral of the result is exactly the lamp function (Figure 7).

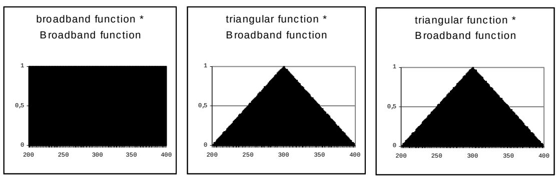


Figure 7. Detector with broadband function (rectangular function), lamp with triangular function.

As the result we can see, that the lamp will be copied into the result, if the detector is rectangular. But normally we do not have a rectangular detector. We have a different spectral distribution detector e.g. a triangular detector.

For a normal used bell (triangular) detector we expect a lower answer of a lamp. The integral of the result is less than the exact lamp function (Figure 8).

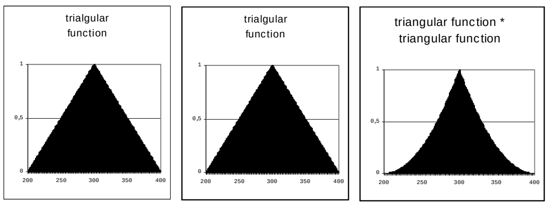


Figure 8. Detector with bell (triangular function), Lamp with triangular function, result as a "hut"-function.

However, from the Example 3 above we could see that also the opposite is possible.

Only with this information "S-L-W-R," "Source-Lamp-Weighting-Radiometer function," you will be able to measure real values. Otherwise your result will be between a factor of 2 which is responsible for an uncertainty of at least 100 %.

Calibration and intercomparison issues with broadband UV meters

Petri Kärhä
Helsinki University of Technology, Finland

Introduction

Ultraviolet sources are often measured with broadband meters, the spectral responsivities of which are matched to follow certain actinic response functions. An example of a broadband meter for UV-region is an erythemally weighted radiometer, which measures the efficiency of UV radiation to produce erythema, i.e. reddening of the skin. An ACGIH meter is similar, but the responsivity function is for a different effect. Very often purely artificial response functions are used. These include e.g. UVA and UVB meters that have a flat responsivity over a certain specified wavelength region. These functions have no real meaning in nature but their definitions are clear, which makes them attractive for many purposes.

The output signal of an ideal broadband meter in source measurements is

$$Response = \int_0^\infty s_{act}(\lambda)\, E(\lambda)\, d\lambda\,, \qquad (1)$$

where $S_{act}(\lambda)$ is the preferred actinic response function, $E(\lambda)$ is the spectral irradiance of the source and λ is the wavelength.

Calibration of broadband UV meters is a complicated problem. The quality of spectral matching of the radiometers is often limited by technology. The true responsivity curve may be far from the theoretical desired actinic response curve. In addition, in practically all measurements, the spectrum of the measured light source varies within the spectral range where the radiometer has significant responsivity. These two things together have a consequence that broadband detectors can not be calibrated without considering the light source that is to be measured. Also uncertainties can only be calculated for a specific measurement, and a certain detector/light source combination.

In this paper, I present three commonly used calibration methods for broadband UV meters. Each calibration method has its own advantages and disadvantages that are discussed. Where possible, guidelines for calculating uncertainties of the calibrations and measurements are given.

Users of UV meters often see that similar meters calibrated in different laboratories show different results. The reasons for this problem are demonstrated with an example. Calibration results for a UVA meter with the three different methods are presented.

Calibration methods for UV meters

There are three possibilities for calibrating broadband UV meters, which are in common use:

1. Calibration using a line source,
2. Spectroradiometric calibration for application, and
3. Measurement of the spectral irradiance responsivity.

Line source calibration

The most common calibration method available in national standards laboratories

The author is with
Helsinki University of Technology
Metrology Research Institute
P.O.Box 3000
FIN-02015 HUT
Finland

E-mail: petri.karha@hut.fi

is a line source calibration. A line source is produced by filtering lines of a Hg-lamp so that only one peak is dominant. This peak may be the 254, 313 or 365-nm peak depending on the meter and the application. With UVA meters the 365-nm line is typically used. The meter under calibration is compared with a reference meter at a known geometrical location in the resulting radiation field.

As the result, one obtains the spectral responsivity of the calibrated meter at the wavelength of the line (e.g. 365 nm) in [A / (W cm^{-2})] or [*reading* / (W cm^{-2})].

This method is relatively simple and fast to perform. Due to simplicity, the calibration is also highly repeatable so it is excellent for stability measurements. Many UV meters are used for measurements of high-power sources, which results in low resolution. For some meters, calibration with a line source is the only option, because other light sources do not produce recordable signal levels.

The uncertainty of the calibration consists mainly of the components arising from

- Calibration of the reference detector,
- Repeatability of the measurements,
- Geometrical factors, like positioning in the beam, and difference between the aperture areas of the two devices,
- Resolution of the calibrated radiometer.

With careful work, a high-quality radiometer may be calibrated with an uncertainty of 3 – 5 % using line sources. However, this low uncertainty gives typically no information on the uncertainty of the measurements using the device, unless it is used for measurements of similar line sources. Two exceptions occur: Radiometers with flat spectral responsivity (e.g. thermal detectors) or radiometers whose responsivity curves are known to be very close to the desired action spectra can be used for high-accuracy measurements with this kind of calibration.

Spectroradiometric calibration

A common method used for calibrations of UV meters used for medical applications is a calibration using a spectroradiometer. This calibration method is a recommended practice e.g. in Scotland [1] and Finland [2].

In this method the meter under calibration is compared with a calibrated spectroradio-meter, using a UV-lamp as the light source. The calibration is obtained for the light source used in the calibration, so the calibration has to be repeated for all light sources that are to be measured.

The measurement results can be used to calculate a correction factor for measurement of the specific light source as

$$CF = \frac{\int_0^\infty s_{act}(\lambda)E(\lambda)d\lambda}{Reading}, \qquad (2)$$

where $E(\lambda)$ is the measured spectral irradiance, *Reading* is the response recorded for the radiometer under calibration, and $s_{act}(\lambda)$ is the desired action spectrum.

Spectroradiometric method gives the calibration for the actual desired measurement situation and enables uncertainty calculations for this specific measurement.

The uncertainty of this calibration consists mainly of the components arising from

- Calibration of the spectroradiometer,
- Repeatability of the measurements,
- Geometrical factors, like positioning in the beam, and difference between the aperture areas of the two devices,
- Resolution of the calibrated radiometer.

Spectroradiometric measurements are more complicated than measurements with e.g. pyroelectric radiometers. This implies that the uncertainty will be somewhat higher than with the line source method. A high-quality radiometer may be calibrated with an uncertainty of 5 – 8 % using this method. In practical measurements one also needs to consider ageing of the meter.

Measurement of the spectral irradiance responsivity

Some national standards laboratories have monochromator-based setups that can be used to measure the spectral irradiance responsivity, $s(\lambda)$, of a UV-meter. The measurement should be performed in over-fill mode to obtain results in [*reading* / (W cm^{-2})].

The resulting irradiance responsivity curve can be used for calculating correction factors for any light source with a known spectrum. The correction factors are calculated using equation

$$CF = \frac{\int_0^\infty s_{act}(\lambda)E(\lambda)d\lambda}{\int_0^\infty s(\lambda)E(\lambda)d\lambda}, \qquad (3)$$

where $s(\lambda)$ is the measured spectral irradiance responsivity of the radiometer and other components are as with Eq. (2).

To calculate the uncertainty of the measurements, uncertainties of the two integrals in Eq. (3) are needed. These arise from

- Uncertainty of the irradiance responsivity measurement, and
- Uncertainty of the relative spectral shape of the lamp spectrum used.

It should be noted that the absolute uncertainty of the lamp spectrum has no effect on the uncertainty. Only the difference between the spectral shapes of the spectrum used in the calculation and the spectrum of the actual light source measured is significant. Other (minor) uncertainty components arise from

- Repeatability of the measurements,
- Resolution and bandwidth of the responsivity data,
- Geometrical factors, like positioning in the beam, and difference between the aperture areas of the two devices,
- Resolution of the calibrated radiometer.

The more the correction factor deviates from unity, the higher the measurement uncertainty. If major part of the response comes from wavelength regions outside the desired action spectrum, spectral changes in the lamp output may cause severe changes in the measurement results.

This method is versatile and gives lots of information about the radiometer. However, the service is expensive and rarely available. The power levels of the monochromator-based light sources of the national standards laboratories are typically in the microwatt-level, which is too low for many industrial radiometers.

Practical considerations

It is often necessary to transform calibrations obtained for a certain light source to correction factors with other light sources. This may be done with methods described in [3] provided that the relative spectral irradiance responsivity of the meter is known. This curve may be measured or it may be provided by the manufacturer of the meter.

If the uncertainty requirements for measurements are not extremely demanding, the spectral irradiances of light sources needed to use Eq. (3) may be taken from literature. Reference [4] lists typical spectra for various UV light sources. These spectra are depicted in Figure 3.

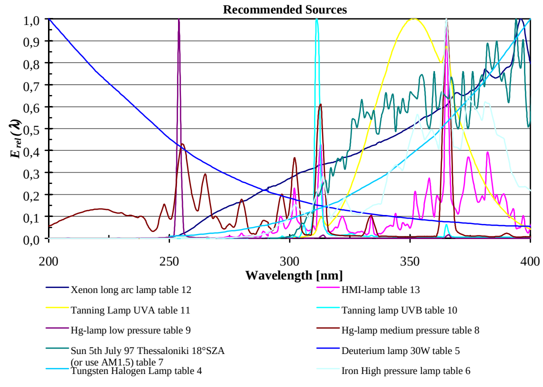


Figure 3. Spectra of the sources used for calculating correction factors [4].

Experimental results

To demonstrate the differences of the different calibration methods, an example is given. A UV radiometer was calibrated at the Helsinki University of Technology using all three methods. According to the description in the manufacturer specification, this radiometer is "a portable instrument that measures ultraviolet light intensity in the spectral range of 320 – 380 nanometers in microwatts per square centimeter (µW / cm^2)." It is further specified that the device has been calibrated using line sources with an uncertainty of 5 %.

The radiometer is intended to be used for measuring the output of a UVAHAND 8 UVA black light source. This light source is used in non-destructive testing, for detecting cracks in material with fluorescing agents.

Calibration using a line source

A line source was produced by imaging a 1-kW xenon arc lamp into a single grating monochromator, and using the out-coming monochromatic field for calibration. The bandwidth of the monochromator was 5 nm, the wavelength was set to 365 nm, and the calibration was obtained by a comparison with a calibrated pyroelectric radiometer.

The ratio of the irradiances measured with the pyroelectric radiometer and the UV radiometer was 1.01. Calibration factor close to 1 indicates that no significant change of responsivity had occurred since the last manufacturer calibration.

Calibration using the measurement source

The UV radiometer was next calibrated with a spectroradiometer using the light source, UVAHAND 8, submitted with the radiometer. The spectral irradiance of the light source was measured at 80-mm distance with a spectroradiometer having a 1-nm bandwidth. The result is presented in Figure 1.

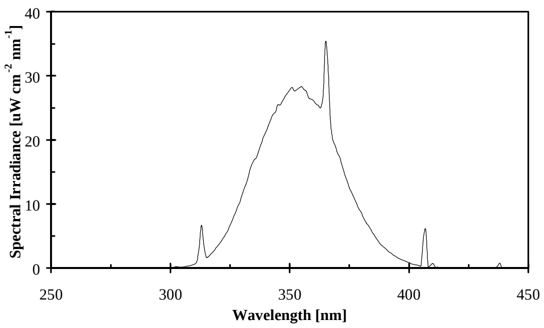


Figure 1. Measured spectrum of the UVAHAND 8 light source.

We choose the target function as the manufacturer has specified – a rectangular function in the wavelength region 320 – 380 nm. This calibration yields to a correction factor of 1.2.

It should be noted that this correction factor is valid only for the UVAHAND 8 light source. No conclusions can be made e.g. on measurements of other light sources. The deviation of the measured correction factor (1.2) from the correction factor measured for a line source (1.01) implies that big systematic errors might occur.

Spectral responsivity calibration

The irradiance responsivity of the radiometer was further measured using the earlier mentioned monochromatic light source. The bandwidth and the calibration step were both set to 5 nm. The results are presented in Figure 2.

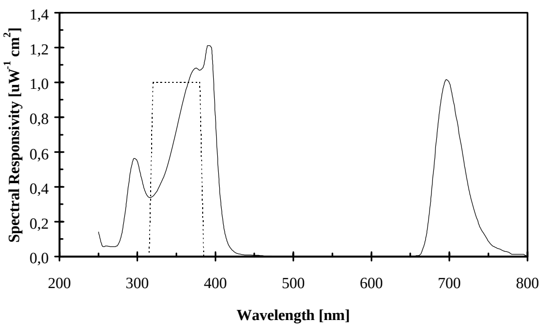


Figure 2. Measured spectral responsivity of the UVA meter (solid line). Dashed line depicts the preferred actinic response, unit responsivity in the wavelength region 320 – 380 nm.

It can immediately be seen that the response function in the UV region is far from the desired rectangular action spectrum. Besides there is a significant infrared leakage in the filter used in the radiometer.

The correction factors calculated for sources in Figure 3 are tabulated in Table 1. In addition, correction factors for the UVAHAND 8 and a 365-nm line source have been included. The integrals have been calculated throughout the wavelength region from 250 to 800 nm.

It may be noted that the correction factors deviate significantly from unity, and that they vary to a large extent from source to source. The more the spectrum of the light source deviates from the spectrum of the 365-nm line source, the more the correction factor deviates from unity. The largest correction is required for a measurement of Tungsten halogen lamp. This is because of the infrared leakage that causes most of the response.

Intercomparisons

Table 1 demonstrates the main reason why intercomparisons show large discrepancies between calibration services. There is no general calibration for UV meters that could be applied for measurements on any light source. The calibration depends on the light source used for the calibration. A successful comparison requires that:

1. All participants use the same calibration method, or
2. All participants specify the way of calibration and co-ordinator converts the calibrations into comparable figures using methods described in [3, 4].

Conclusions

Three different methods in common use for calibrating broadband UV radiometers have been presented. It has been demontrated with an example that the correction factors obtained for different light sources deviate by tens of per cents. UV radiometers therefore can not be calibrated without considering the light source that is to be measured. Comparing calibration services without considering the methods used is of limited value as well.

Table 1. Correction factors for the UVA meter for measurements on various light sources.

Type of source	Correction factor
Xenon long arc lamp	0.32
HMI-lamp	0.72
Tanning Lamp UVA	1.18
Tanning lamp UVB	0.53
Hg-lamp (low pressure)	0.28
Hg-lamp (medium pressure)	0.67
Sun (AM1.5)	0.79
Deuterium lamp 30W	0.67
Tungsten Halogen Lamp	0.06
Iron High pressure lamp	0.77
UVAHAND 8	1.20
365-nm line source	1.01

The quality of the radiometer used as an example was rather poor. The responsivity curve was far from the desired actinic response curve and the radiometer had significant undesired responsivity in the near infrared region. This resulted in large correction factors varying from 0.06 to 1.2. Xu and Huang have recently published a similar survey with UVA radiometers of better quality [5]. Also in this survey, the correction factors varied by approximately 50 % with typical light sources used for UV work. Similar results have been demonstrated by Larason and Cromer [6].

The first recommendation on characterisation techniques for UV-meters has just recently been published [4]. Further work is carried out within CIE [7] to produce an internationally accepted recommendation on the calibration and characterisation methods applicable for broad band UV meters.

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Dosimeter study of pre-school children's UV-exposure – A measurement evaluation

U. Wester[1], C. Boldemann[2], H. Dal[2], W. Josefsson[3], T. Landelius[3], L-E. Paulsson[1], and K. Yuen[1]

[1] Swedish Radiation Protection Authority (SSI), Stockholm, Sweden
[2] Community Medicine (CM) of Stockholm County, Stockholm, Sweden
[3] Swedish Meteorological and Hydrological Institute (SMHI), Norrköping, Sweden

1. Introduction

Solar UV monitoring instruments at SSI in Stockholm have been used to validate dosimeters and a spatially resolved solar UV model system used in a research project to study pre-school children's UV-exposure. The study is a joint effort of the Swedish Radiation Protection Authority (SSI), the Swedish Meteorological and Hydrological Institute (SMHI), and the Community Medicine (CM), Stockholm County.

The evaluation of the dosimeters took place in Stockholm at SSI (59.360°N, 18.050°E), but the study of the children's exposure was performed at two day care centres at other geographical positions in Stockholm County ("Igelkotten" 59.128°N, 18.105°E and "Eken" 59.167°N, 18.151°E). Children at the day care centres wore UV dosimeters in order to assess their UV-exposure and the relevance of different shade structures at playgrounds (Fig. 1).

The dosimeters were commercially available biotechnical dosimeters from BioSense, Germany "Viospore, Blueline type III, 0.8-33 MED". (Here 1 MED = 250 J_{CIE}/m^2 = 2.5 SED). They function by UV-induced DNA-damage to a film of dried bacteria spores (Bacillus subtilis). Together, the bacterial spore film and an optical filter mimic the erythemal spectral sensitivity of human skin. The optics have a cosine-resembling angular response. The manufacturer precalibrated the dosimeters and, after exposure, determined the CIE-weighted erythemal exposure.

Figure 1. Child with dosimeters (Photo: C.B. With permission).

Altogether sixty-three children at the day care centres wore two dosimeters each on their shoulders during a total of eleven predominantly sunny days May 27 – June 12, 2002. Time periods spent outdoors were clocked and recorded for each child every day. Each total individual UV-exposure measured by the dosimeters was related to the available ambient global UV-exposure

The corresponding author is with
Swedish Radiation Protection Authority (SSI)
Div. of Environmental & Emergency Assessment,
Non-ionizing radiation (IJS)
SE-17116 Stockholm
Sweden

E-mail: ulf.wester@ssi.se

for the sum of the same time periods of the eleven measurement days.

Data on the available ambient global UV-exposure at the geographical positions of the two day care centres were provided by SMHI and extracted from a model system for reporting spatially distributed radiation quantities [1]. The system is based on a spectral clear sky model ("UVspec" by Kylling-Meyer), applies satellite measurements of total ozone, recorded data of clouds, precipitation, etc, and produces information about hourly global UV irradiance on a horizontal surface.

2. Evaluation of the dosimeters

Accuracy and variation of dosimeters of the same type as those used by the children were evaluated at SSI. Fifteen dosimeters (BioSense Viospore blue-line type III, 0.8-33 MED) were tested on a roof platform with free horizon. Eleven dosimeters, one at a time, were given one-day exposures from sunrise to sunset on the same days as the ongoing study at the two day-care centres. The results of the dosimeters and of SMHI's model calculations for each day were compared to an average of four of SSI's different solar UV-monitoring instruments that are installed on the roof platform (GUV-541, Scintec UV-S-AE-T, SL501A, Middleton UVR1-B CS). Deviations of these instruments from their average vary, but noontime deviations are usually within 6 %. The SSI instruments have calibrations traceable to an international intercomparison (NOGIC2000) in June 2000 at the Swedish westcoast [2]. An independent calculation with a clear sky radiation transfer model originating from Chicago University (provided by Dr E. Weatherhead, NOAA, USA), carried out four days with clear sky conditions, constitutes a further confirmation of the SSI instrument exposure measurements and SMHI's model calculations (Fig. 2). Later in August additional measurements with an Optronic model 742 laboratory spectroradiometer (absolutely calibrated with a NIST-traceable lamp reference) confirmed that the results of SSI's UV-monitoring instruments were within the temperature dependent expected uncertainty of the spectroradiometer system (approx. -10 – +20 %).

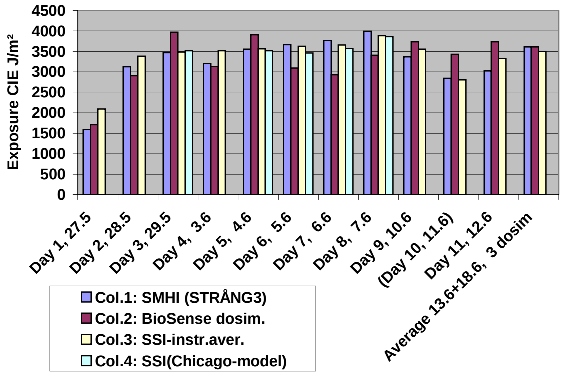

Figure 2. Global daily UV-exposure 27.5 – 18.6, 2002 at SSI roof platform 59.36°N, Stockholm.

According to the SSI-instruments, CIE-weighted erythemal global UV-exposure on the roof platform during the eleven days varied from 2087 to 3877 J_{CIE}/m^2 per day (8.3 – 15.5 MED). Four dosimeters were exposed for the same two full days during which the instruments registered a total of 7478 J_{CIE}/m^2 (30MED).

2.1 Mid- and high dose levels

At the dose-levels (8 – 30 MED) resulting from 1 – 2 full days of Scandinavian summer sun the average relative error of the Viospore type III dosimeters used in the study was < 5 %, but there was a spread of the results of the dosimeters. Two dosimeters were removed from the analysis, having been damaged by rain in the evening on their days of solar exposure (June 11 and 18). The results of these two dosimeters were particularly erratic, +22 % and -35 % respectively. Though all dosimeters were expected to be rainproof, the two erratic ones had been water damaged by leakage according to the analysis of BioSense. When the water-damaged dosimeters had been excluded the remaining dosimeters' extreme deviations were -20 % and +14 % for the measured dose levels.

Results of thirteen of the fifteen dosimeters, ranging from 1702 to 3732 J_{CIE}/m^2 for the one-day exposures and 6533 – 7867 J_{CIE}/m^2 for the two-day exposure, show a high average agreement (mean = -4.6 %, stdev = 12.2 %, n = 13) with SSI's UV-measurements. There is a similar agreement between the dosimeters and the SMHI-model calculations (mean = +0.3 %, stdev = 13.6 %, n = 13). The best agreement (mean = -3.8 %, stdev = 7.8 %, r = 0.96, n = 13) was observed between the SMHI-model calculations and SSI measurements (Fig. 2).

For these samples, the potential information to be derived from correlation coefficients, r, may be limited. For the fifteen dosimeters vs. the SSI-instruments, correlation coefficients > 0.90 can be calculated in the dose range 8 – 30 MED (r = 0.97, n = 13). However, in the limited dose range (8 – 15 MED) applicable to the eleven days of the study the correlation coefficient r = 0.65 only, due to the spread of the dosimeter results. It has been estimated that a small sample implies a large confidence interval for the Pearson's correlation coefficient, r, and makes conclusions less unequivocal concerning the study of the children.

2.2. Low dose levels

At low dose levels, close to the detection limit of BioSense-dosimeters, deviations of 15 – 40 % have been observed for Viospore type I (0.2 – 9 MED) dosimeters [3]. The spread (variance) of Viospore dosimeter values depends on the optical properties of the individual components in the dosimeters and differs from type to type. The spread of type I is claimed by BioSense to be below 10 % when the dosimeters are used at mid- or full capacity. The spread of type III may be more due to a system with more filters [4]. This study has confirmed such a larger spread (stdev 12 % or 14 %) at the upper dose range of type III dosimeters. At their detection limit (0.8 MED) and in a low dose range type III dosimeters might consequently be expected to exhibit deviations and variances even larger than found for type I dosimeters.

2.3 Dose levels of the study

In the study of the children the exposures of the dosimeters was in the low- and mid range of the dosimeters' full capacity (33 MED). Values of the children's dosimeters ranged from 24 – 5350 J_{CIE}/m^2 (0 – 21.4 MED). For a total of 126 dosimeters the mean was 1782 J_{CIE}/m^2 (7 MED), the median 1747 J_{CIE}/m^2, and the standard deviation 966 J_{CIE}/m^2 (54 %).

3. Conclusions for the dosimeter study of children's UV-exposure

As the number of dosimeters used to study the children's UV-exposure is large (>100), a relatively accurate average result can be expected. However, the dosimeters may lack sufficient precision to measure, with statistical significance, all individual exposures or the influence of different shade structures on small subgroups of children at each day care centre. The task of measuring such differences requires high precision (reliability) rather than high average accuracy (validity).

4. Results of the study

Preliminary results indicate that the pre-school children when being outdoors at their day care centres receive approximately 15 % or less of the available ambient UV (free horizon). As expected, data also tend to verify that children at shaded playgrounds might be less exposed than children at less shaded playgrounds. A detailed analysis of data from the study will be reported elsewhere.

5. Postscript and acknowledgements

SSI has funded the project, made the comparative measurements on the roof platform and analysed corresponding data

(Wester, Paulsson, Yuen). SMHI has provided model data for the three sites (Landelius, Josefsson). Community Medicine, Stockholm County has planned, administered and calculated the children's dosimeter measurements (Boldemann, Dal). Staff and children at the two day-care centres helped carry out the measurements.

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Realisation and dissemination of spectral irradiance at NPL

Emma R Woolliams, Neil J Harrison, Boris B Khlevnoy, Leon J Rogers, and Nigel P Fox
National Physical Laboratory, Teddington, United Kingdom

Over the last decade there has been an increasing demand for improved accuracy in the measurement of spectral irradiance and radiance. This has largely been driven by the Earth Observation community for studies of climate change and in particular the Solar UV community, where small variations in UV radiation can have potentially catastrophic consequences for mankind. It is not surprising that it is also within this spectral region that the uncertainties of UV scales disseminated by National Metrology Institutes (NMIs) have also been relatively large, and where significant variations have been observed between their disseminated scales [1]. However, in seeking to improve measurement accuracy it is important to ensure that the goal is "improved accuracy for the user application" and not simply a lower uncertainty in the primary realisation. It is therefore of equal importance to improve the performance of transfer standards for such applications, since instabilities in traditional tungsten halogen lamp sources have the potential to be a major source of error in scales disseminated by NMIs.

Many NMIs have made use of the advent of cryogenic radiometry and the dramatic reduction in uncertainty of resultant spectral responsivity scales together with the availability of ultra-high temperature, high emissivity black bodies to establish new higher accuracy spectral emission scales [2].

The authors are with
National Physical Laboratory
Optical Radiation Measurement Group
Queens Road, Teddington
Middlesex, TW11 0LW
United Kingdom

E-mail: emma.woolliams@npl.co.uk

A few years ago NPL purchased an ultra high temperature black body (UHTBB), model BB3500, from VNIIOFI in Russia to establish a new "detector based" spectral irradiance scale. This new scale is currently being compared to those disseminated by other NMIs as part of the CCPR key comparison K1-a, which is piloted by NPL.

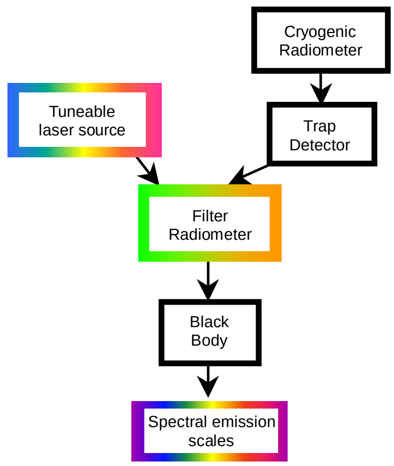

Figure 1. The calibration chain at NPL from the Cryogenic Radiometer to the spectral radiance and irradiance scales.

The UHTBB is capable of operating at temperatures up to 3500 K, making it highly suitable for the realisation of UV spectral irradiance scales. Investigation has shown that it is highly uniform [3] and can be held stably at the required temperature. It is a higher temperature version of the BB3200 source, which has been extensively investigated [4,5].

The spectral radiance of any high emissivity black body source can be calculated using Planck's law from its thermodynamic temperature. At NPL filter-radiometers are used to measure this temperature. Their responsivity is calibrated against trap detectors using tuneable laser radiation. The trap detectors have, in turn, been calibrated against the primary standard detector [6], a cryogenic radiometer. In this way uncertainties associated with realisation of the practical temperature scale, ITS-90, are removed.

The irradiance scale is transferred to lamps using the Spectral Radiance and Irradiance Primary Scales facility (SRIPS). The SRIPS facility can currently cover the range from 250 to 2500 nm. The lamps are calibrated by comparing the signal of the double grating monochromator system when measuring the black body (of known radiance) to the signal when measuring the lamps. In the range from 250 to 300 nm, the original monochromator suffers from "re-entrant spectra" and instead a set of filters is used to transfer the scale from the UHTBB to the lamps. A new monochromator currently under investigation will operate down to 200 nm.

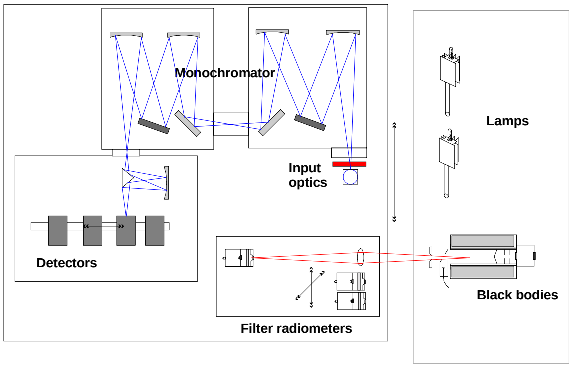

Figure 2. A schematic layout of SRIPS.

An additional problem in the UV is the absorption of some of the radiation by subliming carbon. Peter Sperfeld at PTB [7] first observed this problem with the BB3200 black body. We have also observed absorption lines at UV wavelengths caused by absorption in sublimed carbon at the front of the black body. Figure 3 shows the difference between the ratios of radiance of the black body at 2540 K and the radiance at two higher temperatures compared with those expected from Planck's law. At 2540 K very little carbon sublimes, but as the temperature increases more carbon is sublimed and therefore the absorption is higher. Unfortunately, the reason for operating the black body at these higher temperatures is to increase the UV signal. Therefore this is a significant problem for the realisation of UV scales. In addition a compromise temperature is required for all spectral regions, since emissivity increases with increasing temperature. Further investigations are required to understand the variability of the absorption with temperature and with cavity age so that the effect can be minimised and then quantified.

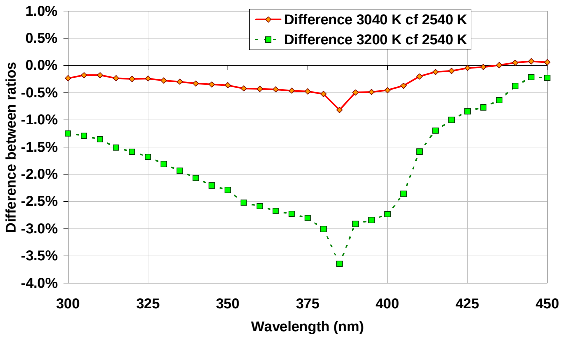

Figure 3. Difference beyond that expected from Planck's equation between the black body radiance at 2540 K and at two higher temperatures. The difference is caused by the absorption of UV in carbon gas from sublimed carbon.

Outside this spectral region, the predominant uncertainties in the spectral irradiance scale, as realised at NPL, are the repeatability of the SRIPS facility between black body and lamp calibrations and the knowledge of the black body temperature, based on the filter radiometer measurements. Figure 4 presents the predominant and overall k = 2 uncertainties for the SRIPS facility as a function of wavelength.

These uncertainties, however, are only the uncertainties in the realisation, onto lamps, of the primary scale at NPL. Arguably one of the more fundamental problems arises from the stability and transportability of standard sources and the length of the traceability chain used to disseminate this scale to end-users. Spectral irradiance scales are often transferred to the end user on FEL-type tungsten halogen lamps. Our investigations have shown that such lamps can often suffer sudden jumps in their output after around 100 on-off cycles and/or after transportation [8]. To reduce the effect of this, we always recommend that lamps be used in groups of three. However, significant benefit can be gained through the use of filter radiometers in conjunction with the lamp. [9,10]

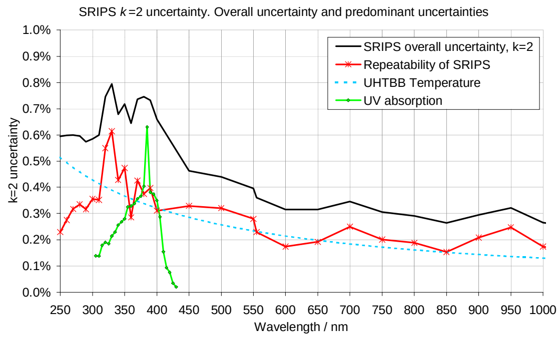

Figure 4. Predominant and overall k=2 uncertainties of the SRIPS facility.

The original NPL detector stabilised lamp (DSL) was based on an FEL lamp in a fully enclosed housing monitored by four filtered detectors. The filtered detectors could be chosen to cover the entire spectral range of the lamp, or could be concentrated in, for example, the UV. One detector provides the signal for the feedback routine, while the others are monitors and can provide immediate information if the lamp output has changed outside its uncertainty limits. The user therefore knows before each use whether the lamp requires recalibration.

The original DSL was complex and therefore relatively expensive. NPL is now evaluating a new, inexpensive, DSL. This DSL is much simpler in operation, while retaining the high colour temperature and performance of the original lamp.

In the future for some highest accuracy applications it may be necessary for end users to have a high temperature fixed-point black body as a reference source. Eutectic black bodies for this purpose are currently under investigation at a number of NMIs around the World [11] and have been made with thermodynamic temperatures approaching 3300 K. These can provide a reproducible and predictable high temperature, high emissivity black body source that will emit enough UV to provide a reference for this region.

New types of transfer standards coupled with improvements to spectral irradiance scales realised at the NMIs are improving the accuracy with which scales are disseminated to the user community. These, together with the results (when known) of the current CCPR key intercomparison of spectral irradiance, may help to answer some of the concerns recently expressed by the solar UV community about apparent discrepancies between lamps calibrated traceably to different NMIs [12]. The key intercomparisons of spectral irradiance organised by the CCPR as part of the Mutual Recognition Agreement (K1-a, 250 – 2500 nm, is currently in progress and K1-b, 200 – 400 nm, will follow it) will fully describe the "degree of equivalence between NMIs." The results will be available on the BIPM website [13] as they become available. It should however be noted that this will of course only be applicable to standards obtained directly from NMIs. Secondary suppliers will have to demonstrate their "degree of equivalence" and justify their uncertainty claims and "traceability" through formal accreditation processes if end users are to benefit from any of the improvements outlined above.

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