

THEMATIC NETWORK FOR ULTRAVIOLET MEASUREMENTS

**Working Group 2: Improvement of measurement and calibration
methods for spectrally resolved UV measurements**

**Improvement of measurement and
calibration methods for spectrally resolved
UV measurements**

APPENDIX

November 2000

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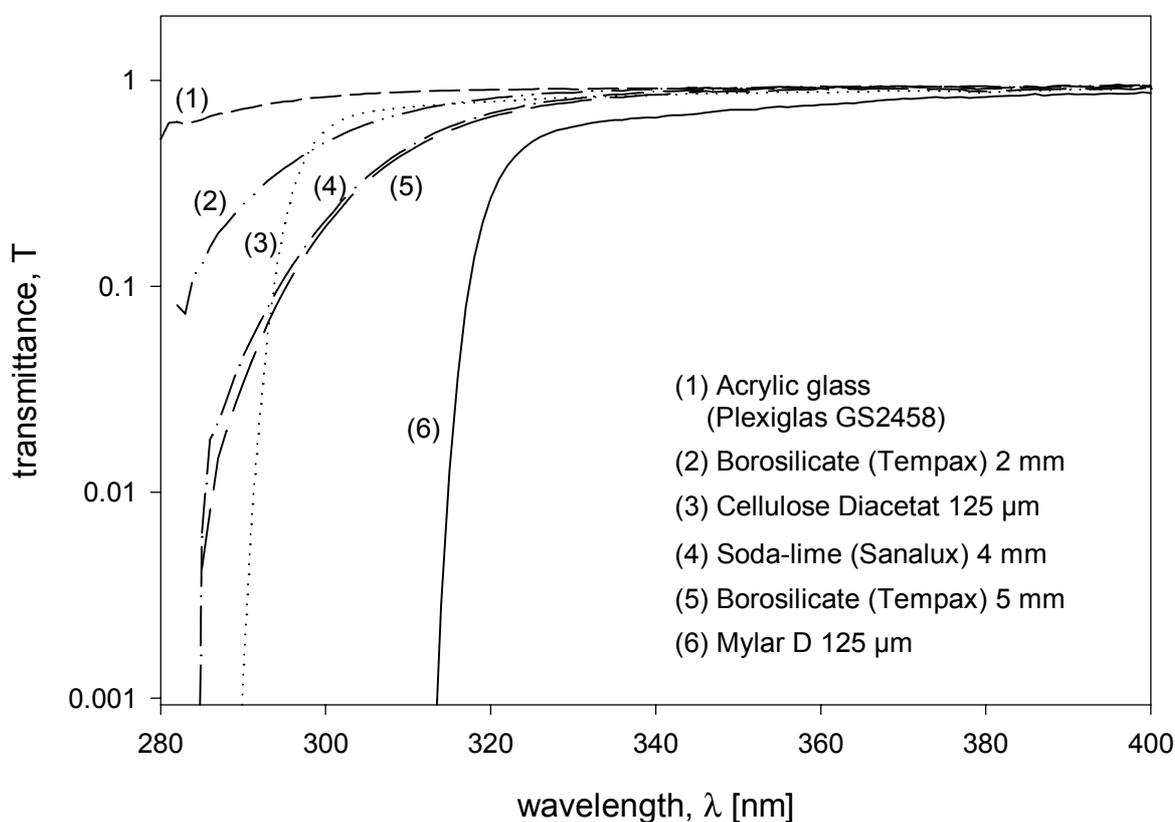
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Appendix 1. Transmittance of UV filters used in solar radiation simulators

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In solar radiation simulators for plant research different filter materials are used for shaping the lower wavelength edge of the spectrum in the UV-B range. Besides polymers and Mylar foils, mainly borosilicate and soda-lime glass filters are employed. The typical spectral transmittance of these materials is shown in the figure as a function of the wavelength. The transmittance was determined as the ratio of spectral irradiances measured with a double monochromator with cosine-like entrance optics that were covered or not with the filter under consideration; the incidence of the radiation was spatially homogenous.



It is well known, that these glass filters show a non-negligible ageing which results in a decrease of the spectral transmittance, mainly in the UV-range of the spectrum. This might originate from UV-induced changes of the oxidation state of iron contaminations inside the glass. Döhring et al. [1] investigated the dependence of the change of the transmittance on the wavelength and irradiation. They used the unfiltered radiation of a certain solar radiation simulator for their experiments. It turned out that soda-lime glasses reach a nearly constant transmittance after pre-ageing. In contrast, borosilicate glasses exhibited a continuous ageing, even after 300 hours of UV-treatment (at approx. 30 Wm^{-2}).

UV-B transparent acrylic glass is often used to expose samples under natural global radiation and at the same time protect them from atmospheric influences. Unexposed sheets show a transmittance of approx. 30 % @ 280 nm. Interestingly after a first exposure (6 – 12 hours @ 30 W/m² UV-B irradiance) the UV-B transmittance increases up to 40 – 50 %. After longer exposure time the process is reversed and the UV transparency degrades continuously (after 60 h @ 30 W/m² UV-B irradiance transmittance is only 10 % @ 280 nm).

Cellulose acetate films are frequently used for shaping the short-wave edge of the spectrum. They exhibit a very sharp cut-off, however their UV transparency degrades rapidly, such that they have to be replaced frequently.

Mylar film is used for UV-B exclusion experiments (e.g. for controls). It has a sharp cut-off at wavelengths between 315 and 320 nm

Also liquid filters can be used to simulate the solar UV irradiation in the laboratory. For example a system of three successive liquid filters containing solutions of copper sulphate, potassium nitrate, and potassium chromate could be used. Due to the different absorption characteristics, it is possible to simulate most natural irradiation situations by combination of varying concentrations of the solutions and thickness of the filter layers. Especially the copper sulphate is very suitable to simulate the cut-off edge of the solar spectrum by ozone absorption. The ageing of these liquid filters is very quick (some hours of UV exposition). One can enlarge the durability of the filter solutions by using a larger volume of the solutions and pumping it through the filters permanently. By this, heating effects due to the lamp can be avoided too.

- [1] Döhring et al., “Spectral Shaping of Artificial UV-B Irradiation for Vegetation Stress Research,” *J. Plant Physiol.* **148**, 115 – 119 (1996).

Appendix 2. Current status of spectral irradiance measurements

Appendix 2.1 Status report of CCPR key comparison CCPR-K1.a “Spectral Irradiance 250 nm - 2500 nm”

N. Fox, NPL, United Kingdom

The CCPR Key comparison on spectral irradiance has been subdivided into two spectral regions, largely to match with user requirement and the nature of the transfer standards used. The first phase of this comparison is in the spectral region 250 to 2500 nm (Tungsten range) and is being organised by the National Physical Laboratory in the UK. The comparison has been arranged so that each participating laboratory will measure the spectral irradiance of a set of at least 3 lamps at a number of predefined wavelengths within a spectral range over which they offer a measurement service.

The lamps will initially be selected and calibrated at NPL before distribution to each laboratory. Each laboratory will measure a set of lamps and then return them to NPL who will re-measure to ascertain any instabilities or changes in the lamps output during transport. Finally the lamps will be returned to the participants who will make a further measurement to complete the sequence.

One of the difficulties in carrying out this particular comparison is the relatively poor performance of the transfer standards available. Participants have therefore been given the option to participate using more than one type of transfer standard, in this way it is hoped that some additional information on the performance of different types of transfer standards may be obtained. The principle type of lamp being used is that of the tungsten halogen lamp (NIST style FEL type), a secondary additional option is of a specially designed tungsten lamp, more rugged but lower operating temperature and thus narrower spectral range. In addition to the above conventional transfer standards each participant will also measure a detector-stabilised lamp. It is hoped that this type of source will allow rapid monitoring of any changes in the performance of the transfer standard as well as improving their long-term stability.

In order to compare the results of each participating laboratory a reference value will be calculated probably based on the weighted mean of all the results. This reference value and in effect the comparison will be determined independently for each wavelength and thus the comparison can really be considered as a large set of separate comparisons. Each participant's results will then be calculated with respect to this reference value.

In carrying out this comparison, as with all Key comparisons, the analysis of the results will require a full uncertainty budget for each wavelength point and each component within it will be subject to review by the CCPR.

The comparison is currently underway with participants from 13 countries and is expected to be completed by the end of 2000, so that the report can be submitted for approval at the next meeting of the CCPR in the spring of 2001.

Appendix 2.2 The uncertainty of the irradiance scale at the user's site

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The primary irradiance standard of a calibration site is the basis on how comparable one's spectral UV measurements are with those of the others. The uncertainty related to this standard was investigated by purchasing the calibration of 1000 W DXW lamps from the following five laboratories offering such a service: Finnish Radiation Protection Authority, Gigahertz Optik GmbH, Swedish Testing and Research Institute, Optronic Laboratories Inc., and Helsinki University of Technology. For most of them the experiment was repeated twice. The laboratories provided the calibration according to their normal procedure applied to any customer. For most of them the experiment was repeated twice.

The spectral response function $R(\lambda)$ of the spectroradiometer is given by Eq. (1) as follows:

$$R(\lambda) = C_{\text{raw}} / I_{\text{cert}}, \quad (1)$$

where C_{raw} = measured lamp raw data and I_{cert} = certified lamp irradiance. The response functions (Fig. 1) obtained from each of the lamps were compared at the laboratory of Jokioinen Observatory, Finland, by measuring the spectral irradiance of each lamp three times successively using a double monochromator Brewer Mk-III #107. The optical axis was vertical, which was also required by the calibration laboratories. The measuring distance was 500 mm. The stability of the instrument was monitored during the entire experiment by using a portable 50 W UV-B Lamp Kit, and by measuring the output of an internal standard lamp at fixed wavelengths in UV-B and UV-A. The wavelength setting of the instrument was checked before each measurement by using the 296,7 nm emission line of an internal mercury lamp. The measurements were performed in a dark room equipped with calibrated electronics and a thermal stabilisation to within $\pm 0,5^{\circ}\text{C}$.

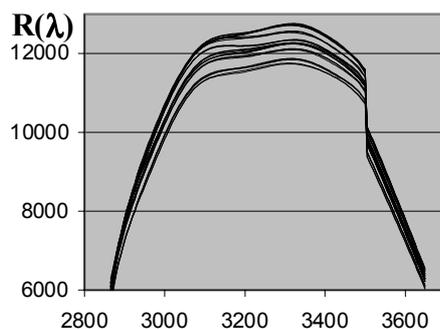


Figure 1. The spectral response functions $R(\lambda)$ obtained from different sources deviate visibly from each other. Here $[R(\lambda)] = (\text{counts/s})/(\text{W}/\text{m}^2/\text{nm})$, and the wavelength axis is in Ångströms.

The stability of each lamp was monitored by recording the voltage drop over the lamp, and by measuring its radiant power with two temperature-controlled broadband silicon detectors, one being sensitive in UV-B and the other in UV-A. All control and environmental information was recorded at a time interval of 2 to 3 seconds.

The results indicate larger differences than expected. In the beginning some individual calibrations suffered from human errors in the certificate data which could only be detected by having other calibrations as a reference. The correction of these errors by the originator was allowed before continuing the analysis. At the end the irradiance scales could differ by up to 10 % through the whole wavelength range even in the case of a common physical laboratory as the origin of the traces (Fig. 2).

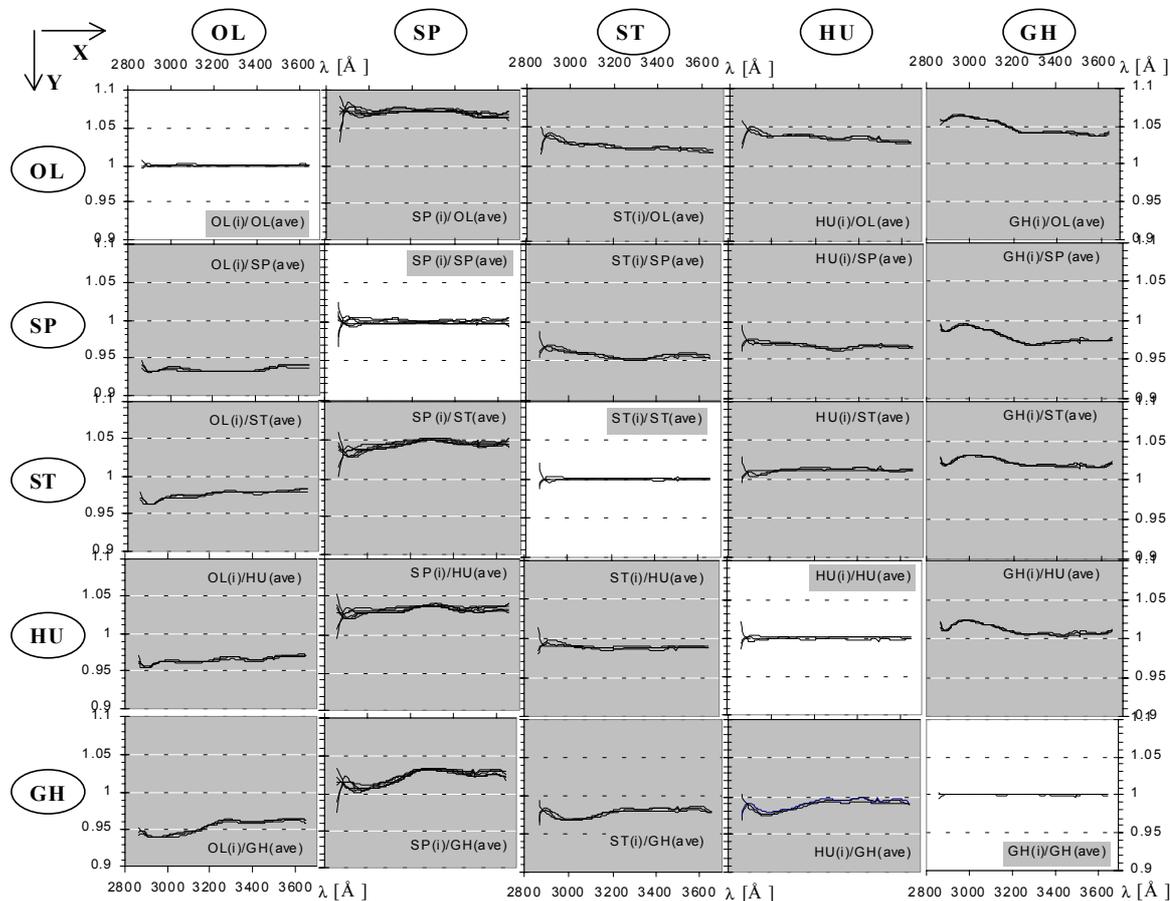


Figure 2. Ratio between the response functions suggested by the laboratory on the X-axis and the average of the response functions suggested by the laboratory on the Y-axis ($= R_i(\lambda)_X / R_{ave}(\lambda)_Y$).

The observed differences may not offer a statistically significant sample for the general estimation of the uncertainty of the primary standard of users' home laboratories. However, they serve as an example on the possible differences in the scales of data sets based on irradiance traces obtained from different laboratories. Consequently, in instrument intercomparison campaigns the trace of each instrument's calibration should be taken into account in more detail: If the majority uses one calibration laboratory, they are more likely to dominate in the determination of a campaign reference although it is hard to say whether they are 'all right or all wrong.' The home data sets of each instrument would probably also benefit from having a calibration obtained from more than one laboratory.

Appendix 2.3 Summary of the present status of the agreed EUROMET Project

H. Rabus, PTB, Germany

The Agreed Euromet Project 437 (AEP-437) "Evaluation of the radiometric performance of UV photo-detectors" was initiated in 1997 as an activity in preparation of the upcoming CCPR Key Comparison K2c of UV spectral responsivity. The project was intended to yield information on the suitability of the then newly developed PtSi/n-Si Schottky photodiodes to be used as sensitive element in transfer detector standards used in comparisons. Furthermore, the participation of three European NMIs with spectral responsivity scales based on cryogenic radiometers operated with different kinds of radiation sources, – lasers, synchrotron radiation, and incandescent or arc lamps – and the inclusion of the NIST was to provide the basis for an informal comparison as precursor of the actual Key Comparison.

The current status of AEP-437 is that bilateral comparisons between NPL and PTB, on the one hand, and NMi-VSL and PTB, on the other, have been performed. The results obtained to date are summarised in Fig. 1 and indicate that there is agreement of the UV spectral responsivity scales of NPL, PTB, and NMi-VSL within the combined standard uncertainties. Additional measurements involving the three NMIs are still on the way, and the measurements at NIST are still to take place before the end of 2000. The target date for completion of the project and the publication of the results in *Metrologia* is planned for early 2001, so that there should be no interference with the CCPR Key Comparison of UV spectral responsivity.

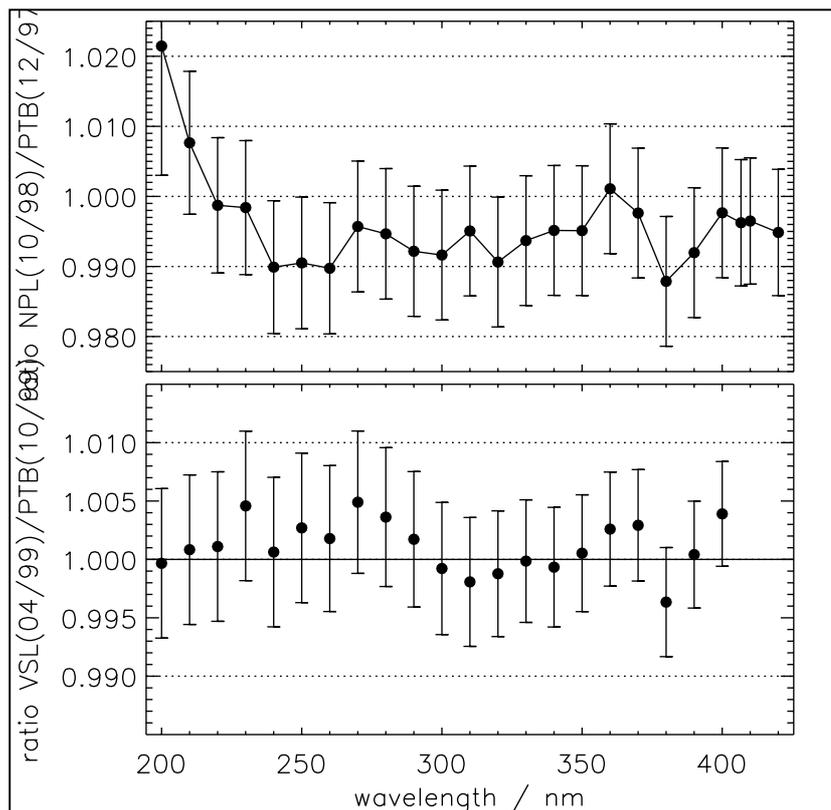


Figure 1. Ratio of the spectral responsivity of a PtSi/n-Si Schottky photodiode as determined by NPL and PTB (top) and of two photodiodes as calibrated by NMI-VSL and PTB (bottom), respectively.

In the latter case the average of the measurements of the two photodiodes is shown. The error bars show the combined standard uncertainty of the respective comparison. The results indicate agreement of the spectral responsivity scales of the three NMIs.

Appendix 2.4 UV Irradiance tungsten-halogen transfer standards

N.J. Harrison, NPL, United Kingdom

1. Conventional tungsten halogen transfer standards

The performance of spectral irradiance transfer standard lamps has long been a concern in the radiometry and photometry communities. In the UV region down to 250 nm, the preferred lamps are tungsten-halogen, quartz enveloped lamps. However, the variability in temporal stability across manufacturers, and indeed between lamps from the same manufacturer, mean that careful pre-selection is required to obtain stable and reproducible transfer standards [1]. Of the many varieties of tungsten halogen lamp in use as transfer standards the 1 kW ‘NIST style’ modified FEL lamp is pre-eminent. The modified FEL lamp generally used as an irradiance standard was originally used as a projector lamp. It has a vertical double-coiled helical filament with the filament supported only at the top and bottom. A middle filament support that exists in the original projector lamp has been removed to improve uniformity. The FEL lamp has the advantage that it is inexpensive, operates at a high distribution temperature and can be used as a spectral irradiance source from 250 nm upwards. The performance of the modified FEL lamp in carefully controlled laboratory conditions has been reported as excellent when operated under a continuous burn regime [1]. However, the majority of the physical stress on a lamp occurs when the lamp is switched on or off. There has been increasing concern as to the performance of the FEL lamp when operated under normal use with many on/off cycles over the course of the lamp lifetime. Additionally, vibration induced changes in the spectral output of such lamps can occur when transported by road or rail. These changes with FEL lamp operation or transport are generally caused by bulk movement of the filament, or by collapse of the internal filament windings, and may not always be apparent in changes to the voltage and current supplied to the lamp, but rather as changes to the spectral profile of the lamp.

In preparation for the CCPR irradiance key comparison between National Measurement Institutes ‘real-life’ testing of over thirty FEL lamps both pre-selected, according to published procedures, and direct from the manufacturer were performed at NPL. Full details of the testing procedure are given in [2].

The simulated use cycle ageing rate of a pre-selected, pre-aged FEL lamp is shown in Fig. 1. This is a typical illustration of the behaviour of an FEL lamp showing a filament coil collapse at 210 hours. It is important to emphasise that the elapsed burn time includes ramp up, stabilising and ramp down time as well measurement time. Therefore, useful measurement time is roughly half the plotted burn time. Ageing rates between different lamps varied significantly with the lamps showing early coil collapse generally giving higher ageing rates. A rate of change of up to 4 % per 100 hours burn time for a pre-aged, pre-selected lamp which suffered coil collapse at a 140 hours accumulated burn time was the highest ageing rate recorded. This compares with reported ageing rates of between 0,2 % and 1 % for lamps with operating lifetimes of 500 hours or more tested under continuous burn conditions [1]. Figure 2 illustrates the problem with coil collapse. Three lamps are shown, one direct from the manufacturers, Osram-Sylvania, and two lamps from commercial suppliers (OMTec and GigaHertz Optik) that have been pre-aged and pre-selected. The coil collapse in all three lamps can be clearly seen. No difference in behaviour was found between the pre-selected and off the shelf lamps in terms of their

ageing rates and coil collapse after an initial ageing period for previously unseasoned lamps. A wide variety of operational parameters were changed such as lamp current, the ramp up/ramp down time, burn time and lamp off time. The conclusion of the tests was always the same, coil collapse at between 140 hours and 250 hours burn time and a much higher ageing rate on a simulated use cycle than observed and reported elsewhere. In terms of lamp on/off cycles coil collapse starts to occur from as few as 100 cycles.

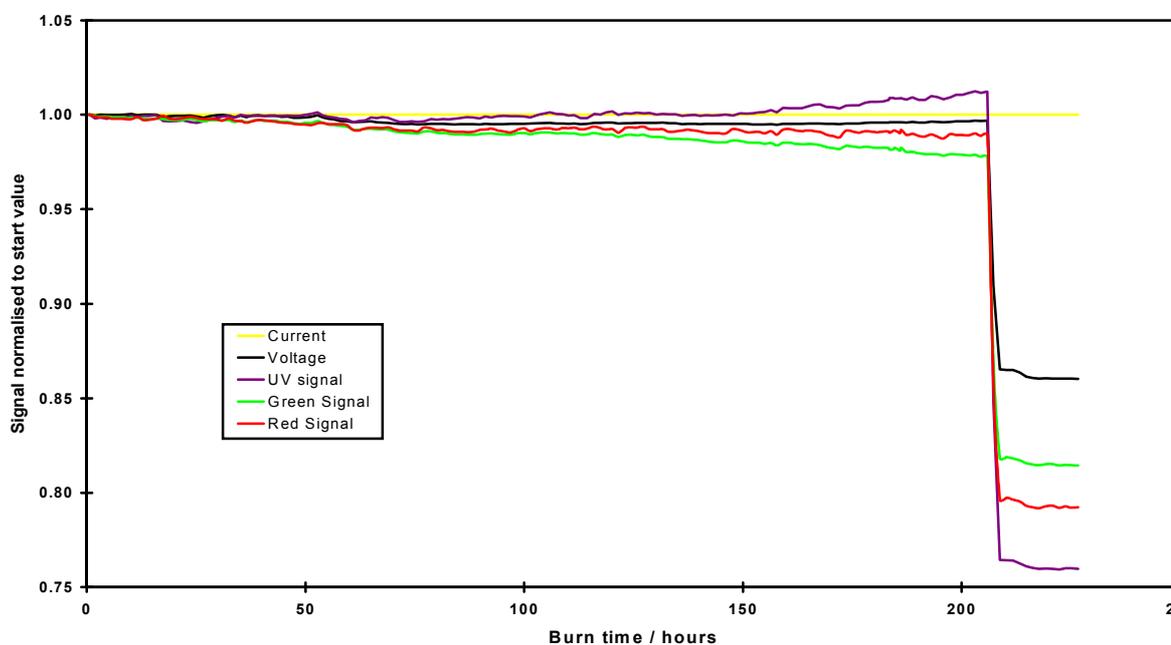


Figure 1. Typical use ageing rate of 'NIST' style pre-aged, pre-selected FEL lamp.

When operated vertically all of the lamps tested suffered terminal coil collapse. Changing the orientation of the lamp burn position to horizontal changed the irradiance levels measured and the spectral shape of the irradiance curve, probably due to changes in the coil conformation. After simulated use cycling the coil sags and contacts the lamp envelope as shown in Fig. 3.

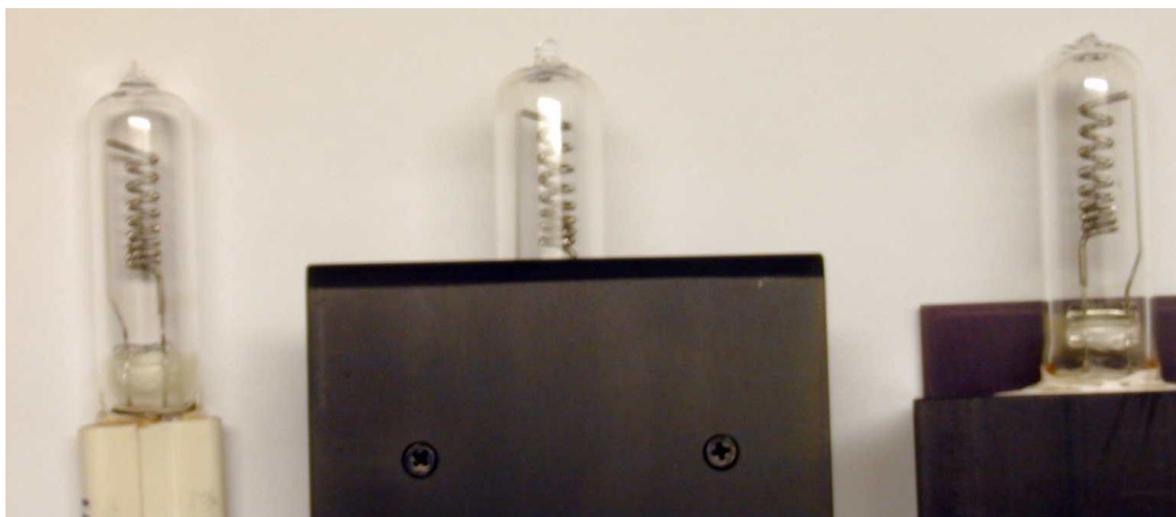


Figure 2. Photograph showing the vertical coil collapse in pre-selected, commercially

available FEL lamps (OMTec and GigaHertz-Optik) plus lamp straight from manufacturer (OSRAM) after normal use cycling.

The reproducibility of the FEL lamps after transportation was also investigated. Road and rail transportation tests were performed. Figure 4 shows typical results for two lamps, each lamp had been pre-aged and pre-selected by a commercial supplier. One plot shows a simple level change that probably results from a change in the filament position. The other plot shows a significant spectral change after transportation. Both results give cause for concern. Typically, road or rail transportation changed the output of over 1 in 3 lamps tested. It is important to note that because a lamp did not exhibit any significant change upon the first road or rail journey it did not indicate that the lamp was robust as changes could often be seen after further transportation.



Figure 3. Photograph showing sagging of filament and damage to lamp envelope in a horizontally operated ‘NIST’ style FEL lamp operated on a normal use cycle.

The effects of transportation may also explain some of the results reported in [3]. Differences of over 10 % between calibrated lamps from several sources are reported. Even the lamps calibrated and supplied by NIST show differences higher than the quoted uncertainties of the calibration.

2. Detector stabilised irradiance sources

Detector and filter technologies have been shown to have high temporal stability, even in the demanding UV region. Improvements in detector technology have meant that operation from the UV through to the mid-infrared is now possible in small, cheap and stable packages. Even when combined with an appropriate filter to define a spectral band, the stability of the resulting filter radiometers can be maintained after initial solarisation and ageing effects have occurred [3]. Linking cheap, robust and stable detector technology to an irradiance standard lamp, such that the lamp current is adjusted to maintain a constant signal on a monitoring detector, should dramatically improve the stability of the irradiance generated by the lamp. Changes in the electrical characteristics of the lamp, ageing of the lamp envelope, changes in coil conformation, transportation effects etc., can all be compensated for by detector stabilisation.

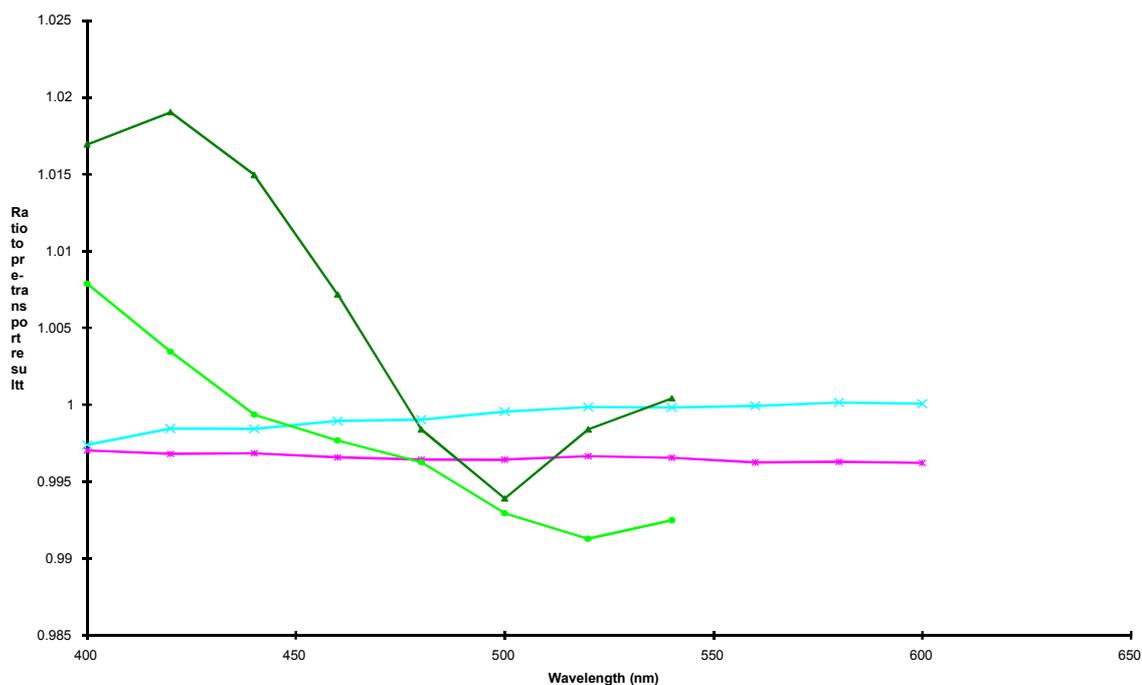


Figure 4. Graph showing the changes in lamp irradiance after transportation.

The new NPL detector stabilised lamp (NPL-DSL) shown in Fig. 5 goes a long way towards achieving this goal. This NPL-DSL incorporates up to four filter radiometers, which continuously monitor the state of calibration of the lamp. These filter radiometers may be selected to achieve the maximum wavelength coverage for general spectral irradiance transfer standards; or more tightly selected for particular applications, for instance for the calibration of a solar UV spectroradiometer, where the particularly fast ageing of standard lamps can cause significant problems.

The continuous monitoring of different wavelength channels gives a profile of the state of calibration of the lamp, allowing sudden changes in calibration to be noted instantly, rather than at the time of data analysis. In the NPL-DSL, the detector stabilisation uses the signal level from one of the detectors as the driving parameter in a feedback loop, which adjusts the lamp current to maintain a constant photodiode signal level. The ability to stabilise using any of the photodiodes provides added flexibility. Stabilisation using the UV channel for instance would provide the most stable transfer standard in the UV-blue region, and since the output of high power tungsten-halogen lamps is approximately Planckian, much smaller current changes are required to maintain the output in this region than at longer wavelengths, leading to better overall maintenance of calibration [4, 5].

The NPL-DSL is a development of our prototype described in [5] and is similar in concept to the OMTec TSS-1000 [4]. Other than differences in the details of the detector arrangement, software etc., the main difference between the NPL-DSL and the OMTec system is that the NPL-DSL is a fully enclosed system, which has the added benefit of drastically reducing the amount of stray light that is present within the laboratory, while providing the rigid geometry required for successful detector stabilisation. The fully enclosed nature of the lamp naturally presents the challenge of the significant amounts of heat, which must be absorbed and dissipated by the lamp housing, without affecting the operation, or life-span of the lamp contained inside. This is achieved by our design. It is

also important to maintain the monitoring filter radiometers at a constant temperature. In the NPL-DSL this is achieved by a Peltier cooler attached to the detector block which is thermally insulated from the main lamp housing.



Figure 5. Photograph of the NPL Detector Stabilised Lamp

The lamp source in the NPL-DSL is typically a 1 kW FEL lamp, although different lamps could be incorporated. The signal on the monitoring photodiode is maintained using a PID loop that controls the output current from a computer controlled power supply. Full details and construction of the lamp are given in reference [6].

After initial ageing under UV stabilisation for 125 hours (5 % change in red signal over the first 50 hours, then a further 0,75 % change over the next 75 hours), the lamp was allowed to burn continuously for 250 hours, the photodiode signals (post ageing) and lamp current changes are shown in Fig. 6. The output of the lamp was monitored using a 407 nm filter radiometer (FWHM 10 nm) mounted a distance of 600 mm away from the exit aperture of the lamp. Readings were taken from this filter radiometer every 30 seconds. Over this operating period, ageing rates of less than $1,6 \times 10^{-5} \text{ h}^{-1}$ were observed across the visible. The external filter radiometer, which has a wavelength close to the stabilisation channel, showed deviations of less than $\pm 0,1 \%$ over the total 250 hours burn time. This would indicate that the measurements, and therefore corrections made by the internal SiC detector were very stable over this time period.

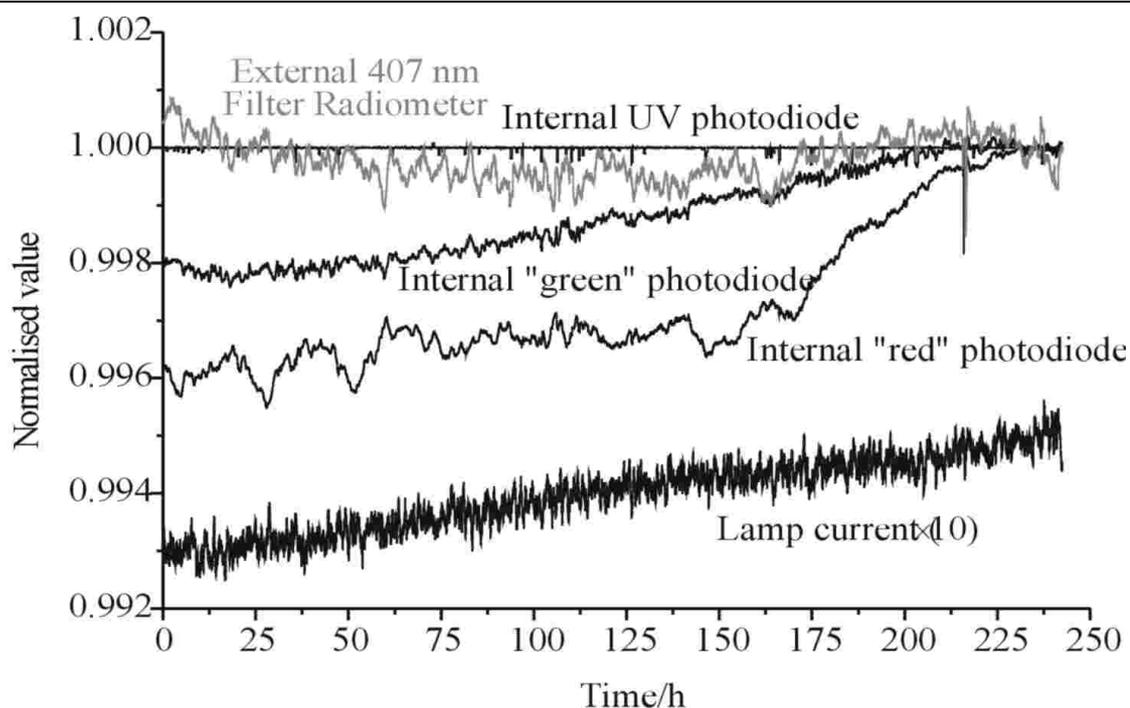


Figure 6. Long term ageing of NPL Detector Stabilised Lamp. Very good long-term stability is observed. Shown are the relative internal photodiode signals, external filter radiometer signal, and the lamp current variations (relative change $\times 10$).

3. Conclusions

Tungsten halogen transfer standards are still some way from providing the calibration accuracies desired by the user community. The performance of the modified FEL lamp in normal usage and after transportation is a major source of concern but more tests need to be performed to confirm the published findings, particularly more rigorous transportation tests. Detector stabilisation shows great promise for improving the dissemination and comparison of scales.

4. References

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- [2] Harrison N. J., Hobbs E. R., Fox N.P., *Metrologia* (to be published).
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- [5] Fox N.P., Chunnillall C.J., White M.G., *Metrologia* **35**, 555-561 (1998).
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Appendix 2.5 Array spectroradiometry - Pulsed UV sources

A.J. Page, Cathodeon Ltd., United Kingdom

At the working group meeting of the UV Thematic Network in September 1999 at NPL, Teddington UK, I agreed to look into the subject of spectroradiometry of pulsed UV sources. From own experience not very much information is in the public domain. Few people at the meeting knew of any work being carried out.

In trying to find more information in this area the first thing that I have done is to identify industrial applications of pulsed UV and the types of UV source used.

Firstly, the most common type of source I have identified regarding industrial pulsed applications is the pulsed Xenon discharge lamp sometimes referred to as a Xenon “flashlamp”. This lamp category covers many actual lamp types and should not be confused with the many types of dc Xenon arc lamp.

1. Applications of pulsed xenon lamps

The following list is not intended to be an exhaustive list containing all known areas. I have just attempted to identify areas which may lead us to be able to find existing measurement information or help define applications that could benefit from further studies.

- Pulsed UV Spectrophotometry - Analytical Chemistry Instrumentation manufactures / laboratory applications.
- Pulsed UV surface treatment
- Pulsed UV sterilisation
- Industrial UV curing
- Pulsed UV curing of medical devices
- Pulsed UV curing of CD's and DVD's
- Semiconductor photostabilisation
- Pulsed UV/VUV semiconductor applications
 - Pre-ion implantation
 - Rapid photothermal processing
 - Surface modification
 - Pre-Dice protective coat curing
 - Surface cleaning
- Solar simulation lamp for scientific systems

2. Photo-diode array instrumentation

Having discussed PDA Spectroradiometry with staff at the NPL there seems to have projects involving PDA's but only in the measurement of CW sources and systems. As far as I have been able to establish, very little has been done regarding the subject of pulsed UV measurement.

I have found that Multichannel Instruments AB of Sweden have an advanced PDA system and have measured pulsed Xenon lamps with 0,5-microsecond resolution between scans. Upon contacting them to see whether they knew of any groups working on pulsed array Spectroradiometry they explained that they produce the equipment mainly for Laser Induced Breakdown Spectroscopy and that the measurements were just conducted to demonstrate the abilities and performance of their systems.

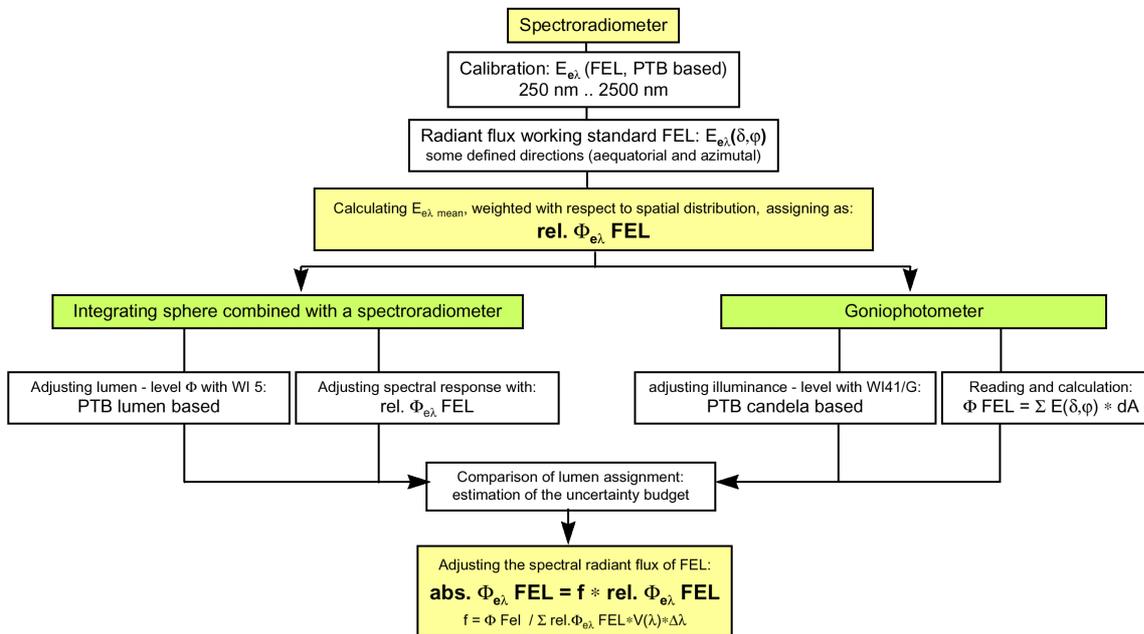
It is entirely possible that Pulsed PDA Spectroradiometry measurement standardisation would be of help, particularly in the semiconductor industry. However, I have not been able to locate anyone in my limited search that could confirm this. If the WG-2 have further interest in this subject then we are going to need to approach contacts in these application areas.

If anyone in the UV Thematic Network has knowledge of this subject, or has contacts that may be able to help, then I would be very interested to hear from them.

Appendix 2.6 Calibration of spectral radiant flux (4π)

W. Steudtner, W. Jordan, W. Halbritter, OSRAM GmbH, München, Germany

Calibration procedure of spectral radiant flux (4π) in UV-VIS-IR at OSRAM laboratory TB/L-M



Spectral calibration (2 m sphere) with such an FEL and measuring a PTB calibrated fluorescent lamp yields a luminous flux within the uncertainty budget given by PTB.

UV-Calibration-Fluss03.ppt

UV thematic network WG 2

OSRAM

Appendix 2.7 Some notes and suggestions on “best practice” for operation of Deuterium Lamps as Standard Lamps

A.J. Page, Cathodeon Ltd., United Kingdom

In the following I have attempted to provide some background information on Deuterium Lamp operation with respect to operating the lamp as a “standard lamp” for spectroradiometry. This is intended to perhaps help discussion for formulation of “best practice” documents.

1. Background

Deuterium Lamp manufacturers offer a wide range of lamps tailored for specific applications. Cathodeon offers lamp types for standard lamps with an internal ‘baffle’ structure to prevent internal reflections thus providing a ‘true’ point source. Other manufacturers devices need external ‘baffles’ to accomplish the same effect.

All widely available commercially manufactured Deuterium Lamps have a similar type of internal structure. The purpose of this structure is to confine the discharge in such a way that only the stable ‘positive column’ portion of the discharge can be viewed by the instrument. There are subtle variations in the structure to optimise the lamps performance within specific applications. All of the above deuterium types share a fundamentally similar type of cathode regime. However there are again subtle variations which require individual attention. The thermionic emitter (cathode) in a deuterium lamp is the source of electrons for the discharge. Its surface interacts with the discharge in such a way as to define the ‘arc’ path. Variations in the arc geometry lead to changes in anode voltage given that the discharge is operated in a constant current mode, usually set between 150 and 300 mA, thus leading to variations in power level within the discharge and subsequent variations in lamp output.

2. Cathode structures.

Commercially available deuterium lamps mostly use a triple oxide cathode. This cathode most commonly takes the form of a directly heated tungsten spiral coated with a triple oxide mixture (Barium, Strontium, Calcium - mixed oxides). The spiral structure is usually of the form of a ‘double’ or ‘triple’ coil. The coils are designed to operate up to a maximum voltage for ‘striking’ the discharge. Lamps are usually designed to fit into two lamp specifications: 10-Volt heater or 3-Volt heater lamps. These types of directly heated structure are relatively simple to manufacture but result in a complex cathode geometry from the point of view of the arc attachment point. Some lamp manufacturers offer an indirectly heated design. This follows the same approach that was used in thermionic valve design. The coil structure containing the triple oxide thermionic emitter is maintained but is heated by an internal metallic sleeve. Inside the sleeve is an electrically isolated heater element. This type of structure has the advantage of more uniform heating of the emitter material. However, the overall result is has limited benefits due to the fact that the Cathode geometry is still as complex as that found in the directly heated designs.

3. Background to modern lamp design

The deuterium lamp has mostly been designed to meet the performance requirements of instrumentation in the Analytical Chemistry market. Applications such as UV spectrophotometry, liquid chromatography, HPLC, atomic absorption spectrophotometry background correction. The performance requirements for these applications have been - Output, Output stability, long life, 'easy' starting.

Switch on repeatability in terms of UV output has not been perceived as such a vital requirement. This is of course an extremely important requirement for a lamp used as a standard lamp for UV spectroradiometry.

As mentioned above the cathode geometry plays a role in determining the output of the lamp. If the lamp operates with emission coming from a certain point on the complex geometry cathode structure this sets the arc path so that once the lamp has warmed up the lamp runs stable on this point. If however this site becomes less active, the anode voltage may increase leading to an increased ion bombardment of the cathode surface. This can lead to further damage or modification and can also then lead to another emission region on the cathode becoming effectively more emissive than the first. When this occurs the arc attachment point may shift to the new site. Depending on the level of emission and the geometrical location of the new site there may be a step change in arc path, anode voltage and therefore UV output.

Selection of different emissive sites on the cathode can also of course occur on 'switch on.' Thus the level of 'switch on' reproducibility is limited for a particular lamp.

4. Best practices to try to improve 'switch on' reproducibility.

Firstly, I should mention that there are different ways of operating a deuterium lamp that may yield different results in respect of the above.

A. The heater voltage level 'pre-strike' conditions

Generally speaking if a deuterium lamp is specified as having a 10-volt filament, this is the level to which the filament should be heated before striking. The amount of time required before applying a strike pulse or anode voltage should be in the 30 - 150 second region. If after only a very short time period the strike voltage is applied the thermionic emission is limited and the strike can result in cathode surface damage. If too long a period of time, i.e. several minutes, is left before applying a strike pulse too much barium will be evaporated off cumulatively after many strikes. The lamp internal gas pressure will also increase which is a negative aspect in terms of striking the lamp.

Deuterium lamps can continue to be operated once the discharge has been initiated in a 'cold cathode' mode, i.e. once the discharge is underway the heater supply is turned off thus relying on the anode current to sufficiently heat the cathode to provide electron emission. This type of operation is not generally recommended. Ion bombardment heating of the cathode surface will continually modify the surface, therefore stable emission sites will have limited life times. This will tend to lead to poor long-term stability performance and thus poor 'switch on' reproducibility.

Another issue to consider is whether to use AC or DC heater supply and the level of the heater current during discharge operation. This is perhaps of more importance in terms of stable operation of the lamp but does have a bearing on the formation of active sites on the cathode surface over the life of the lamp. When a deuterium lamp operates with an AC heater supply, the arc attachment on the cathode surface tends to spread over a larger area - i.e. emission is more diffuse. The more the AC heater current is increased the more diffuse this arc attachment region becomes. An obvious balance is needed here since if the cathode is run at too high a level for too long, too much barium will be evaporated from the cathode leading to life deficiency. The downside of AC operation is that highly active geometrically fixed emission sites do not tend to form as with DC operation and thus shorter term noise is not generally as low as for DC heater operation.

DC heater operation, particularly in 10-Volt deuterium lamps, has the effect of diffusing the discharge, again depending upon voltage level. It also tends to electrically bias the discharge to one end of the filament. If the lamp is aged with the Earth return (anode supply) and negative of the heater supply at one end of the filament, then this will invariably lead to the arc attachment being confined to this end. If this polarity is swapped then it can take up to 250 hours of discharge operation to change to the opposite end and become as stable as the original operating condition. If subsequent reversals are made this process tends, I believe, to speed up over hundreds of hours.

B. Anode current level.

In terms of general stability most deuterium lamps are designed to run at 300 mA, chosen on the basis of a stable operating point on the discharge Voltage/Current characteristic of the given structure. However, to increase the life of the device operation at lower currents is possible without too great a reduction in stability provided the correct heater conditions are met. In general, reduction of the discharge current to around 250 mA may be beneficial, again dependent upon balancing the conditions in terms of applied heater current.

5. Summary

On a 10-Volt deuterium lamp AC and DC heater current operation can provide high stability operation. In terms of operation in analytical equipment where short-term stability over the period of a day is most important, DC heater current operation tends to be accepted as the best practice. However, things are considerably less clear when it comes to 'switch on' reproducibility. This is an area that I think could benefit greatly from further investigation. From our experience, it may well turn out to be "best practice" to age the lamp using DC heater current and then operate the lamp in the "Standards laboratory" in AC heater current mode at an appropriate level.

Appendix 2.8 Typical example of work instructions for spectral irradiance calibration at the PTB

W. Möller, PTB, Germany

1. Brief description of the calibration method

The calibration of spectroradiometric units in an NMI is determined by three main steps: realisation, maintenance, and dissemination.

Especially, the spectral irradiance could be realised by three different ways: related to the Planck's law realised in a black-body radiator, related to the Schwinger equation describing the radiation of an accelerated charged particle realised in an electron synchrotron, and related to the equivalence between electrical and optical power realised in an absolute detector calibration.

In the air-UV, visible and IR spectral region a realisation using a black-body radiator is preferred. The calibration of the absolute spectral irradiance $E_{\lambda}(\lambda)$ of a radiator consists in the spectral comparison, under well-defined and identical measurement conditions, between the irradiance of an unknown radiator (lamp) and the known irradiance of a primary standard via a reflection standard of as completely diffuse a reflection as possible (plane or sphere) in the working plane. The absolute value of the spectral irradiance of the black-body radiator in the plane of the reflection standard can be calculated from the spectral radiance of this black-body radiator at the known temperature T and the solid angle of the black-body radiation defined by the area A of the output aperture of the black-body and the distance d between this aperture and the surface of the reflection standard.

The realised unit is maintained by a transfer to reference or working standards. The reference standard used, in general, is one of a set of calibrated quartz-halogen lamps whose data have been directly traced back to the absolute data of the black-body radiator, which is, therefore, the national standard. The absolute measurement of the measurand thus becomes a relative measurement.

Standard lamps and lamps to be tested are in the same measurement position; therefore, the same optical path is used for both lamp types. This eliminates the influence of the angular dependence of the reflection of the reflection standard, which requires that different reflection directions are used for direct comparison measurements.

The radiometric inverse square law:

$$\frac{E_{\lambda,1}(\lambda)}{d_1^2} = \frac{E_{\lambda,2}(\lambda)}{d_2^2} \quad (1)$$

must be taken into consideration when the distances (d_1 , d_2) between the radiation sources and the reflection standard differ.

A calibration facility contains an element for spectral dispersion and a detector system in addition to the radiators and the reflection standard. An additional monitor lamp is useful to check the stability of the facility.

Spectral dispersion is achieved with the aid of a double monochromator to reduce stray light, the measurements being carried out either with photomultipliers (PMT), photodiodes or photoresistors, depending on the spectral range.

As the lamps must not be moved while they are burning and the measurement over a spectral range takes a prolonged period of time, it is useful to control the stability of the arrangement with the aid of a monitor lamp. The only condition for this arrangement is that all the critical components in the optical path of the standard lamp measurement should be used during the monitor lamp measurement, too. As the calibration of the monitor lamp against a set of standard lamps takes place staggered in time, the operating time of the standard lamps required for the measurement can be considerably reduced compared with the direct comparison, because larger numbers of lamps to be calibrated are compared with the monitor lamp. The standard lamps are thus protected, bearing in mind that the lamps' usability for calibrations is limited by their operating time. Thus in a first measurement the spectral photocurrent $i_{RS}(\lambda)$ of a reference standard lamp (*RS*) is directly compared with the photocurrent $i_{Mon,RS}(\lambda)$ of the monitor lamp at the same wavelength and in a second cycle of measurement the photocurrents $i_{TS}(\lambda)$ of transfer standard lamps (*TS*) will be compared with the photocurrent $i_{Mon,TS}(\lambda)$ of the monitor lamp. The spectral irradiance $E_{\lambda,TS}(\lambda)$ of a transfer standard (*TS*) is obtained from the known irradiance $E_{\lambda,RS}(\lambda)$ of the reference standard (*RS*) and the ratio of the photocurrents $i_{TS}(\lambda)$, $i_{Mon,TS}(\lambda)$ of transfer standard and monitor lamp, which are measured within a short time interval (change from standard to monitor lamp), and the ratio of the photocurrents $i_{RS}(\lambda)$, $i_{Mon,RS}(\lambda)$ of reference standard and monitor lamp, which are also determined within another very short time interval:

$$E_{\lambda,TS}(\lambda) = E_{\lambda,RS}(\lambda) \cdot \frac{i_{TS}(\lambda)}{i_{Mon,TS}(\lambda)} \cdot \frac{i_{Mon,RS}(\lambda)}{i_{RS}(\lambda)} \quad (2)$$

The mean values of several single measurements and measurement cycles are used to determine the spectral irradiance of the lamps to be calibrated. The stability of the monitor lamp's radiation with time is additionally checked with the aid of a monitor detector known to be much more stable with time so that several lamps can be calibrated with a single data set of the reference standard. Almost equal values of the photocurrents of standard and monitor lamp are chosen to avoid additional uncertainties of measurement due to possible non-linearities of detector at the monochromator exit and amplifier.

During calibration, the lamps concerned are operated at constant current. The lamp currents and the distances $d_{1,2}$ between reference standard or the lamp to be tested and the reflection standard are reference values which influence the result of the calibration [Eq. (1)].

2. Preparations

A. Object to be tested

- The lamp to be calibrated must be mounted in a support in such a way that the lamp can be reproducibly adjusted with respect to position, tilting and rotation of the support or with the aid of an adjusting device (jig) which can be plugged in the support. This applies in analogy to lamps installed in a lamp housing.

- Lamp base, lamp support or lamp housing must be of sufficient temperature stability.
- The lamps must have the stable electric characteristics required for calibration, because these characteristics correlate with the stability of the radiator properties. Prior to calibration, brand-new lamps must be pre-aged under operating conditions (sometimes as much as 100 h) while the electrical operating data and the relative irradiance are continuously recorded up to a point in time which corresponds to the foreseeable future performance (depending on the type of lamp).
- The lamp bulb must be clean or it must be cleaned using non-radiation-absorbing agents. It must not show any burnt-in impurities and mechanical damage, such as scratches. Experience has shown that white crystallisations in the lamp bulb material less than 1 mm in diameter, which may occur after several hours of operation, do not change any more or only to an extent which is negligible from the metrological viewpoint. Their number in the direction of radiation should not, however, increase to more than two to three.
- Facilities must be provided on the lamp base, lamp support or lamp enclosure, which allow the supply lines and potential leads to be connected for the purpose of lamp voltage measurement. Screw-type terminals with porcelain body are best suited.
- The polarity of the lamp terminations must be identified.

Upon submission,

- the lamp to be calibrated is checked and the lamp type is compared with the data of the calibration order;
- the applicant's specifications are checked for completeness; they should correspond to those given in the preliminary estimate of cost unless other agreements were made;
- the lamp together with its support or enclosure are checked visually for compliance with the conditions of calibration capability.

After submission,

- the preliminary estimate of cost and the order of calibration are registered and placed in the file with all correspondence, which is to be made up for each order;
- the object to be tested is safely stored prior to and after calibration until it is returned to the applicant.

B. Calibration device

- Before the calibration of a group of lamps is started, the wavelength of the monochromator is calibrated with the aid of spectral line sources.
- Depending on the wavelength range in which the calibration is to be carried out, an exchange of the detector and subsequent adjustment may be necessary.
- The components essential for the measurements, such as mirror, reflection standard,

slit, apertures and shutters are checked visually.

- The electrical connection of standard lamp and lamp to be tested is checked with due regard to polarity.
- The adjustment of the lamps in relation to the optical axis is checked with respect to distance, height, tilting and rotation.
- It should be cared for special needs of detector systems (cooling system, chopper).
- For lamps whose ionising radiation generates ozone, a device for sucking off the air around the lamp must be provided at a distance sufficient to ensure that the measurements are not disturbed.

C. *Measurement and data reduction*

- Check for completeness, arrangement and functional capacity of the measurement devices and PC
- Check of the connecting leads
- Provision of measurement and data reduction software
- Run-in period of measuring arrangement and power supply units (lamps, PMT) for temperature stabilisation: at least 5 hours.

D. *Limiting conditions*

Care should be taken that during calibrations

- ceiling luminaires (especially fluorescent lamps) are not switched on,
- no person stays in the area of the lamps,
- no stronger draught of air is caused by the opening of doors or the like, and
- the ambient temperature does not rise by more than 2 K due to the heating effect of the lamps and power supply units.

3. **Carrying-out of the calibration**

Two groups are formed for the calibration of a set of 4 to 6 lamps. Three standard lamps are measured against the monitor lamp: before, between and after the measurement of each group of lamps. This allows at the same time a possible deviation to be detected due to any defects or due to ageing of one of the three standards.

A burn-in time or a temperature stabilisation of at least 30 minutes is necessary as well for the lamps as for the remaining instruments of the facility. The lamps are used at a constant current during the calibration. This current should be reached by a continuous increase (ramp) from zero current to the defined current within about 1 minute. An abrupt switch on

or switch off will affect or even destroy the stability and burning behaviour of the lamp.

Every spectral lamp measurement is carried out at least twice. In each case, the photocurrent of the standard lamp (or of the lamp under test), the dark current, the photocurrent of the monitor lamp and the corresponding dark current are measured at each individual wavelength and with the same slit width before the next wavelength is selected.

In the wavelength range from 200 nm to 400 nm a solarblind photomultiplier and from 250 nm to 800 nm a broadband photomultiplier is used as a detector whereas a large-area Ge- or InGaAs-photodiode is used in the range from 800 nm to 1600 nm. In the range from 1500 nm to 2500 nm, the signal of a PbS photoresistor chopped with 120 Hz is measured with the aid of a lock-in amplifier.

In the measuring range of the photomultiplier, exceeding of the maximum permissible photocurrent of 2 μA is prevented by attenuation of the signal through variation of the slit; in the other ranges, the geometric slit width is 2 mm (corresponding to a spectral bandwidth of 3,3 nm) to maintain a large signal-to-noise (S/N) ratio. When a higher spectral resolution is required, smaller slit widths will be chosen, provided the S/N ratio - which is then smaller - can be approximately compensated by an increase in the number of measurements per mean value. With the exception of the changes in the slit widths, the measurement sequence is completely computer-controlled as is the printing and storage of the mean values of all measurement data including their standard deviations.

4. Check measurements

Results are checked by different calibration measurements in comparison with the monitor lamp calibrated with independent standard lamps; the measurement results obtained with them must correspond with one another upon evaluation.

5. Evaluation of the measurement results

The data obtained in different measurements of the same lamp are once more combined by averaging and calculated according to the formula given in Eq. (2) for the determination of the spectral irradiance. The result is plotted in a graph. To make checking and a better evaluation of the curve shape possible, the ratio temperature of the spectral distribution is determined and the relative spectral irradiance at this temperature calculated for a black-body radiator and compared with the evaluated values. The shape of this new, plotted curve makes deviations of the spectral lamp radiation from that of a black-body radiator evident. Reasons for such deviations are transmission and absorption of the lamp bulb and gas filling, the emissivity of the tungsten filament and possible outliers of the measurements. These typical deviations are known for the quartz-halogen lamps used as standard lamps and can thus be used as aids for evaluation and checking.

6. Storage and safekeeping

A. Lamp standards

The lamp standards and the lamps to be tested are properly kept in cabinets.

B. Calibration documents

Inquiries of customers, cost estimates, applications for calibrations, calibration certificates, bill of costs, lists in which the costs are recorded and the accompanying letters are chronologically collected in files and kept in a locked steel cabinet in the room of the head of the section. Measurement records, documents for evaluation, and the respective plots are chronologically collected in files and kept in a locked steel cabinet in the room of the person responsible for the calibration.

C. Floppy disks

Floppy disks with the measurement and evaluation programs, with measurement data and evaluations and the respective backup copies are kept in suitable boxes in the room of the facility.

7. Uncertainty determination

The influence which the measuring instruments, the optical, electro-optical and electronic components, the environment and the staff exert on the measurand and the uncertainty of measurement within the scope of realisation, maintenance and dissemination differs. The most important influence quantities have been compiled in the following:

Defining quantities

- primary standard
 - **temperature of the black-body (BB) radiator**
 - geometry (area A of output aperture of BB; distance d to reflection standard)

Lamp standard

- lamp current (and lamp voltage to check stability)
 - measuring resistor (calibrated)
 - digital voltmeter (DVM)
 - distance: lamp \Rightarrow reflection standard

Measuring method

- wavelength
 - **wavelength adjustment**
 - spectral purity
 - reduction of second order spectrum (cut-off filter)
 - slit width (bandwidth)
 - scattered light (single, double monochromator)
- transfer of measurand
 - method
 - optical setup
 - transfer steps [lamp standard \Rightarrow transfer standard (object to be tested)]
 - background radiation
 - stability with time of the facility between change of lamps
 - spatial reproducibility upon change of lamp
 - linearity (detector, amplifier, DVM)

- **signal-to-noise ratio (S/N)**

Change in the standards

- lamp standards
- **operating time after calibration (ageing)**
- switch-on and switch-off operations
- movement while burning
- reflection standard
- keeping of standards

Environmental conditions

- temperature
- atmospheric pressure and humidity
- dust (air condition system)
- extraneous light (kind of signal amplification)
- measurement rooms
- use of rooms for other purposes
- separation of parts of the arrangement

Staff

- expertise
- carefulness
- no change in the staff carrying out the measurements
- introduction

Documentation

- measurement data
- overall uncertainty of measurement
- environmental conditions
- test engineer
- history of the standards

The influence of the individual parameters on the measurand and the uncertainty of measurement were investigated in detail during installation of the measuring arrangement and during the measurements. It turned out that the uncertainty of the measurement result is almost exclusively determined by four influence quantities (bold-faced in the above list). The influence of the other parameters is less critical for the present arrangement and use, and they are, therefore, checked only occasionally.

Among the quantities that essentially influence the uncertainty of measurement, are the following:

- uncertainty with which the temperature of the black-body radiator can be determined,
- ageing of the lamp standards,
- uncertainty with which the wavelength can be adjusted on the monochromator, and
- the signal-to-noise ratio of the detectors (statistical uncertainty of measurement).

Black-body temperature is radiometrically measured with absolutely calibrated broad-band filter detectors. This method allows the measurement uncertainty upon determination of the temperature to be reduced compared to a pyrometer determination of the same temperature.

The remaining three most important influence quantities, too, can be directly investigated within the section. They are recorded either directly during the measurement (S/N ratio) or operation (ageing of lamps), or at defined time intervals (wavelength calibration), and documented in the test record or separately.

Appendix 3. Examples of uncertainty evaluation

Appendix 3.1 Evaluation of the uncertainty of measurement: Calibration of a lamp used as a standard of spectral irradiance

J. Metzdorf, S. Galal Yousef, S. Winter, PTB, Germany

1. Introduction

The evaluation of the uncertainty of measurement based on the principles laid out in the *Guide to the Expression of Uncertainty in Measurement* published by ISO [1] is becoming more and more important for calibration certificates, international comparisons and the establishment of quality systems in order to provide for the mutual recognition of calibration and measurement certificates.

The procedure for calculating the uncertainty of measurement in the case of spectroradiometric calibrations is rather complex, especially if the evaluation of the uncertainty budget has to be in accordance with the respective documents *GUM* [1] of the ISO and *EAL-R2* [2] of the EAL (European co-operation for Accreditation of Laboratories). Based on a general calibration procedure, the following example may be used as a lead-in to the evaluation of the uncertainty of measurement in the calibration of a standard lamp. The uncertainty analysis of a specific calibration of standards of spectral irradiance will be published separately [3].

The unknown spectral irradiance in the reference plane on the optical axis of a lamp is determined by substitution using a spectroradiometer and a calibrated lamp (of the same type) as a reference standard of spectral irradiance (substitution method; see Fig. 1). The spectral responsivity of the (UV) spectroradiometer $s_{\text{Sp}}^{\text{S,X,M}}(\lambda)$ is determined by its components and the optical arrangement. The spectroradiometer consists of a diffuser (integrating sphere or plane reflection standard), a double (grating) monochromator and a detector (photomultiplier) with amplifier and DVM. In addition, the spectroradiometer is monitored by using a (detector-stabilised) monitor lamp, thus, improving the reproducibility of the spectroradiometer typically by a factor of three (monitor technique). The stabilised monitor lamp (without separate external calibration beforehand) is used in a fixed position without any re-alignment uncertainty.

The unknown and the standard lamps are aligned (6 degrees of freedom) in turn at the nominal distance on the optical axis of the spectroradiometer. The lamps are allowed to stabilise before the measurement ($\approx 0,5$ h).

Recording the spectra of spectral irradiance, the spectral irradiance produced by the standard or the unknown lamp are directly compared with the spectral irradiance of the monitor lamp at each discrete wavelength. In order to reduce drift influence, it is recommended to measure the spectra of the standard (S) and the unknown lamp (X) in the following sequence: SXXS SXXS...

During the comparison of the standard or the unknown lamp with the monitor lamp at each discrete wavelength ($t_{\lambda_i} < 1$ min), drift and temperature effects can be considered to be

insignificant.

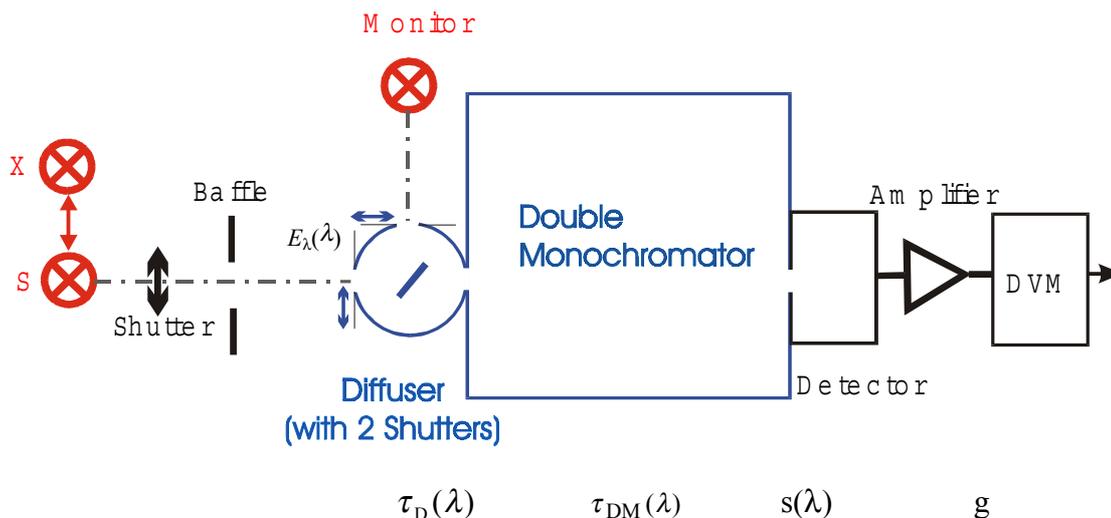


Figure 1. Schematic of the measuring system.

$$\text{Typical measuring cycles} \left\{ \begin{array}{l} \text{X/M}_X \text{ comparison } (\lambda = \lambda_i = \text{constant}) : t_{\lambda_i} < 1 \text{ min} \\ \text{S/M}_S \text{ comparison } (\lambda = \lambda_i = \text{constant}) : t_{\lambda_i} < 1 \text{ min} \\ \text{comparison of spectra } (\lambda_1 \text{ to } \lambda_n) \text{ X/M}_X \text{ with S/M}_S : t_{\lambda_i, \lambda_n} > 1 \text{ h} \\ \text{(possibly at different days)} \end{array} \right.$$

According to the measuring cycles carrying out X/M_X comparisons and S/M_S comparisons, different monitor data M_S and M_X have to be taken into account.

2. Model of evaluation and calibration equation

The signals (voltages) at the (digital) read-out of the spectroradiometer produced by the incident spectral irradiance of unknown (index X) and standard lamp (index S) are obtained from the relationship¹:

$$V^{S,X} - V_0 = (E_{\lambda}^{S,X}(\lambda) + E_{\lambda,b}^{S,X}(\lambda)) \cdot \Delta\lambda(\lambda) \cdot s_{Sp}^{S,X}(\lambda) \quad (1)$$

with $s_{Sp}^{S,X}(\lambda) = \tau_D^{S,X}(\lambda) \cdot \tau_{DM}^{S,X}(\lambda) \cdot s^{S,X}(\lambda) \cdot g^{S,X}$.

Shadowing the direct and only the direct radiation of the lamps by inserting a suitable shutter, the signals caused by the stray or background radiation are given by:

$$V_b^{S,X} - V_0 = V^{S,X} (E_{\lambda}^{S,X}(\lambda) = 0) - V_0 = E_{\lambda,b}^{S,X}(\lambda) \cdot \Delta\lambda / \lambda \cdot s_{Sp}^{S,X}(\lambda) \quad (2)$$

The respective signal produced by the monitor lamp (index MS or MX or, in general, M) is obtained from the relationship:

¹ Temperature dependence (of all quantities) within the short measuring times t_{λ_i} can, in general, be neglected and is not explicitly taken into account reducing the number of corrections.

$$V^M - V_0 = E_{\lambda}^M(\lambda) \cdot \Delta\lambda(\lambda) \cdot s_{Sp}^M(\lambda) \quad (3)$$

with $s_{Sp}^M(\lambda) = \tau_D^M(\lambda) \cdot \tau_{DM}^M(\lambda) \cdot s^M(\lambda) \cdot g^M$

The following symbols of input and output quantities are used including corrections for systematic effects:

$V^{S,X,M}$	signal for the standard, unknown or monitor lamp;
V_0	offset of detector (including dark current), amplifier and DVM (both shutters of the diffuser closed);
$E_{\lambda}^{S,X,M}(\lambda)$	spectral irradiance produced by standard, unknown or monitor lamp in the respective reference plane of the diffuser (input port of integrating sphere or plane surface of reflection standard);
$\delta E_{\lambda,D}^{S,M}(\lambda)$	change of the spectral irradiance of the standard or monitor lamp since its last calibration due to drift;
$\delta E_{\lambda,C}^{S,X,M}(\lambda)$	correction of the spectral irradiance of the standard, unknown or monitor lamp due to deviations from nominal operating conditions (temperature, lamp current);
$\delta E_{\lambda,A}^{S,X}(\lambda)$	spectral irradiance correction due to misalignment of the standard or unknown lamp (6 degrees of freedom: distance from reference plane, 2-dim. displacement from the optical axis, 3 angular deviations); comment: re-alignment uncertainty of the fixed monitor lamp is zero;
$\delta E_{\lambda,R}^S(\lambda) = \delta E_{\lambda,R}^X(\lambda)$	spectral irradiance correction $\delta E_{\lambda,R}(\lambda)$ due to non-normal incidence on the reference plane of the diffuser;
$E_{\lambda,b}^{S,X}(\lambda)$	spectral irradiance due to background radiation and stray radiation produced by standard or unknown lamp;
$\lambda = \lambda_i$	discrete nominal wavelength of the monochromator;
$\delta\lambda_i(\lambda_i, \Delta\lambda, T, \partial E_{\lambda}/\partial\lambda)$	difference between nominal and centre wavelength due to the calibration procedure including drift, slit function, room temperature variation and slope of (relative) spectral irradiance; the difference in the relative spectral distribution of the irradiance has to be considered especially if FEL-type and deuterium lamps are compared;
$\Delta\lambda(\lambda), \delta\Delta\lambda(\lambda)$	effective FWHM of the slit function of the monochromator, where FWHM is also slightly dependent on the change of the

	slope $\partial E_{\lambda}^{S, X, M}(\lambda) / \partial \lambda$ resulting in $\delta \Delta \lambda(\lambda) = \Delta \lambda^S(\lambda) - \Delta \lambda^X(\lambda) \neq 0$;
$s_{Sp}^{S, X, M}(\lambda)$	spectral responsivity of the spectroradiometer altogether with respect to the spectral irradiance produced by standard, unknown or monitor lamp;
$\tau_D^{S, X}(\lambda)$	spectral transmittance of the integrating-sphere diffuser (spectral reflectance of a plane diffuser), where the entrance port is irradiated by standard or unknown lamp;
$\delta \tau_D(\lambda)$	correction of the diffuser transmittance $\delta \tau_D(\lambda) = \tau_D^S(\lambda) - \tau_D^X(\lambda) \ll \tau_D^{S, X}(\lambda)$ due to the influence of temperature, irradiance or ageing effects (fluorescence in the UV?);
$\tau_D^M(\lambda)$	spectral transmittance of the diffuser (sphere), where the monitor port is irradiated by the monitor lamp;
$\delta \tau_D^M(\lambda)$	change of the spectral transmittance of the diffuser due to drift and ageing between the calibrations of the unknown (X) and the standard lamp (S); in general, conditions (measuring cycles) prevail that $\delta \tau_D^M(\lambda) / \delta \tau_D(\lambda)$ is constant and $\tau_D^S(\lambda) / \tau_D^M(\lambda) = \tau_D^X(\lambda) / \tau_D^M(\lambda)$;
$\tau_{DM}^{S, X, M}(\lambda)$	spectral transmittance of the double monochromator, where $\delta \tau_{DM} = \tau_{DM}^S - \tau_{DM}^X$;
$\delta \tau_{DM}^M(\lambda)$	correction of the monochromator transmittance due to drift and change of temperature between the measurement of the unknown and that of the standard lamps, where $\delta \tau_{DM} / \tau_{DM}^{S, X} = \delta \tau_{DM}^{MS, MX} / \tau_{DM}^{MS, MX}$
$s^{S, X, M}(\lambda)$	spectral responsivity of the detector at the exit slit of the monochromator $s^{S, X, M}(\lambda) = s(\lambda) + \delta s^{S, X, M}(\lambda)$;
$\delta s^{S, X, M}(\lambda)$	correction of the spectral responsivity for non-linearity due to different radiant power levels produced by standard, unknown or monitor lamp; contributions caused by drift and temperature variation can be neglected because they can have an effect only measuring times $t_{\lambda i} < 1$ min;
$g^{S, X, M}$	gain of amplifier and DVM $g^{S, X, M} = g + \delta g^{S, X, M}$;
$\delta g^{S, X, M}$	correction of the nominal / observed gain for non-linearity and limited resolution of the DVM at the respective levels due to

standard, unknown or monitor lamp.

Thanks to the monitor technique, the calibration result depends upon ratios of input quantities using data obtained within short times ($t_{\lambda_i} < 1$ min), thus reducing the effects of temperature variation and drift.

The following ratios (here without indices and argument λ) are used in addition:

$$\sigma^{S,X} := \frac{s^{S,X}}{s^{MS,MX}},$$

where $\frac{\sigma^S}{\sigma^X} \approx 1 + \delta\sigma$;

$$\gamma^{S,X} := \frac{g^{S,X}}{g^{MS,MX}},$$

where $\frac{\gamma^S}{\gamma^X} \approx 1 + \delta\gamma$.

Because of the fact that only the differences of the deviations (linear approximation) enter into the respective relationships, correlated contributions of systematic effects of the detector, amplifier and DVM do not markedly influence the result. Thus, the standard uncertainty of the resulting correction factors is determined only by uncorrelated deviations.

The spectral irradiance $E_{\lambda}^X(\lambda)$ of the unknown lamp in its reference plane [see Eqs. (1) to (3)] is obtained from the relationships:

$$v_{\lambda_i}^{S,X} \Big|_{\lambda_i} = \frac{V^{S,X} - V_b^{S,X}}{V^M - V_0} = \gamma^{S,X} \frac{(E_{\lambda}^{S,X} + \delta E_{\lambda}^{S,X}) \cdot \Delta\lambda \cdot \tau_D^{S,X} \cdot \tau_{DM}^{S,X}}{(E_{\lambda}^{MS,MX} + \delta E_{\lambda}^{MS,MX}) \cdot \Delta\lambda \cdot \tau_D^{MS,MX} \cdot \tau_{DM}^{MS,MX}} \cdot \sigma^{S,X} \Big|_{\lambda_i + \delta\lambda_i^{S,X}} \quad (4)$$

with abbreviations

$$\delta E_{\lambda}^{S,X} = \delta E_{\lambda,D}^S + \delta E_{\lambda,C}^{S,X} + \delta E_{\lambda,A}^{S,X} + \delta E_{\lambda,R}$$

$$\delta E_{\lambda}^M = \delta E_{\lambda,D}^M + \delta E_{\lambda,C}^M$$

$$\delta\lambda_i^S = \delta\lambda_i^X \ll \lambda_i ,$$

if standard and unknown lamp are of the same type.

Although $\delta\tau_{DM}^M$ and $\delta\tau_{DM}$ may not be neglected, the ratios $\tau_{DM}^X / \tau_{DM}^{MX} = \tau_{DM}^S / \tau_{DM}^{MS}$ are identical in practice.

Introducing the ratios of the signals produced by standard or unknown lamp on the one hand and the signals produced by the monitor lamp on the other hand, the measuring equation is written as:

$$\frac{v^S}{v^X} \Big|_{\lambda_i} = (1 + \delta\gamma) \frac{(E_\lambda^S + \delta E_\lambda^S)}{(E_\lambda^X + \delta E_\lambda^X)} \cdot \left(1 + \frac{\delta\Delta\lambda}{\Delta\lambda}\right) \cdot \left(1 + \frac{\delta E_\lambda^M}{E_\lambda^M}\right) \cdot \left(1 + \frac{\delta\tau_D^M}{\tau_D^M}\right) \cdot \left(1 + \frac{\delta\tau_D^X}{\tau_D^X}\right) \cdot (1 + \delta\sigma) \Big|_{\lambda_i + \delta\lambda_i} \quad (5)$$

Without taking the (linearly approximated) correction factors explicitly into account, the resulting **calibration equation** can be written as:

$$E_\lambda^X(\lambda_1) + \delta E_\lambda^X(\lambda_1) = \frac{v^X}{v^S} \Big|_{\lambda_1} \cdot (E_\lambda^S(\lambda_1) + \delta E_\lambda^S(\lambda_1)) \quad (6)$$

In summary, the correction factors (not to be confused with uncertainties) are due to the following effects and changes occurring between the measurement of the standard lamp (S, M_S) and that of the unknown lamp (X, M_X):

$\delta\sigma, \delta\gamma$	any nonlinearity, drift or temperature effect of the detector responsivity and of the gain of amplifier and DVM;
$\delta\Delta\lambda/\Delta\lambda$	relative change of the effective bandwidth if the relative spectral distribution of standard lamp and unknown lamp are markedly different;
$\frac{\delta\tau_D^M}{\tau_D^M}, \frac{\delta\tau_D^X}{\tau_D^X}$	respective relative changes of the spectral transmittance (or reflectance) of the diffuser;
$\frac{\delta E_\lambda^M}{E_\lambda^M}$	relative drift and change of the spectral irradiance of the monitor lamp.

3. Outlook

The next steps after expressing the calibration equation and identifying all significant corrections are mainly

- an extended listing of typical measurement results (input data) and explanations and comments to the different quantities and corrections;
- an uncertainty budget in table form including the evaluation of the statistical parameters (distinguishing between repeatedly measured quantities and single values): for each quantity and correction an estimate, assigned standard uncertainty, probability distribution, sensitivity coefficient and uncertainty contribution have to be given;
- furthermore, the statement of the expanded uncertainty and the reported complete result of measurement is straightforward.

The analysis of a specific measurement setup (spectroradiometer) is needed for the evaluation of the uncertainty budget. This has been done separately [3] to be published bilingual in German and English, where it was necessary to prepare different tables of uncertainty budgets for different wavelengths/spectral ranges.

Finally, it is pointed out that according to the linear approximation in the deviations, none of the input quantities are considered to be correlated to any significant extent. This approximation should be justified for the evaluation of the uncertainty budget of the spectral irradiance of a standard lamp both at an individual, discrete wavelength and at neighbouring wavelengths possibly correlated in part. This approximation for the determination of independent, uncorrelated spectral data may, however, may no longer be valid if, e.g. the uncertainty of weighted or integrated spectral data (integrated with or without weighting factor) has to be evaluated (see, e.g. the calibration of solar cells or of filter radiometers). In this connection, the following agreement of the CCPR Key Comparison Working Group may be of interest (see Second Meeting, 27 October 1999): On analysis of spectral comparisons we agreed that we should treat each wavelength point as a separate comparison for analysis purposes. If the comparison was a valid one, any variations this approach may produce in the Key Comparison reference value across the wavelength range of the comparison would be less than the expected variation between individual laboratories.

4. References

- [1] *Guide to the Expression of Uncertainty in Measurement*; first edition, 1993, corrected and reprinted 1995, International Organization for Standardization (Geneva, Switzerland).
- [2] *EAL-R2 and EAL-R2-S1: Expression of the Uncertainty of Measurement in Calibration*; Documents produced by the European Cupertino for Accreditation of Laboratories; Edition 1, 1997.
- [3] K.-H. Raatz, K.D. Stock, P. Sperfeld, W. Kessel, "Uncertainty Analysis for Spectral Irradiance Calibration of Thermal Radiators," *PTB report PTB-Opt-xx*, 2000/2001.

Appendix 3.2 Uncertainty budget of detector-based spectral irradiance measurements

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1. Measurement method

The basic concept of detector-based filter radiometry is to transfer an accurately established spectral responsivity scale realised by using a cryogenic radiometer into a spectral irradiance scale.

At HUT, the detector-based method for measurement of absolute spectral irradiance is based on a filter radiometer whose components are characterised separately. The filter radiometer is composed of a trap detector, a set of temperature-controlled band-pass interference filters and a precision aperture [1, 2]. In the measurements, the filter radiometer is placed at a given distance d from the filament of the tungsten-halogen lamp. The output current of the filter radiometer is recorded at several wavelengths, which are selected from the continuous spectrum of the lamp by using a set of band-pass filters. As the result, the measured values of spectral irradiance are obtained at discrete wavelengths in between whose the spectrum is interpolated by using the modified Planck's radiation law.

2. Uncertainty budget

To the obtained values of spectral irradiance their uncertainties are associated. The uncertainty budget of the measurements of absolute spectral irradiance is shown in Table 1. All uncertainty components are presented as 1σ -values. The detailed discussion on the uncertainty budget can be found in Ref. [2]. For that reason, a brief overview of larger components of uncertainty is given below.

Detector responsivity is obtained at a high level of accuracy by using the cryogenic radiometer at visible wavelengths. Larger uncertainties at shorter wavelengths are mostly due to transfer of the absolute responsivity scale from the visible to the near UV spectral interval by using a pyroelectric radiometer.

The uncertainty induced by the filter transmittance measurements includes five components. To evaluate the effects of the first three components, a model of rectangular shape of the spectral transmittance of the filter has been used. The height and the width of the rectangle are considered to be equal to the transmittance value at the effective wavelength and to the full-width at half-maximum of the filter, respectively. The component due to the uncertainty in the out-of-band leakage measurements has been obtained as a relative contribution to the measured signal, when the components of combined out-of-band transmittance are varied by the resolution of the spectrometer. The standard uncertainty in the distance setting at HUT is 0,1 mm. The stated uncertainty component in the value of spectral irradiance is given for the distance of 500 mm, which is an often value of the distance used in the measurements of 1-kW FEL-type lamps.

Table 1. Uncertainty components [%] of the spectral irradiance measurements.

Effective wavelength [nm]	291	302	315	333	352	382	441	501	572	599	698	801	902
Detector responsivity	0.67	0.67	0.54	0.51	0.51	0.26	0.07	0.07	0.07	0.07	0.07	0.07	0.06
Cryogenic radiometer	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Reflectance modelling	-	-	-	-	-	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.02
IQE modelling	-	-	-	-	-	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Spectral flatness of pyro	0.50	0.50	0.30	0.30	0.30	0.15	-	-	-	-	-	-	-
Repeatability	0.40	0.40	0.40	0.40	0.40	0.20	-	-	-	-	-	-	-
Current measurement	0.20	0.20	0.20	0.10	0.10	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Nonlinearity	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Filter transmittance	0.97	0.46	0.37	0.31	0.31	0.36	0.18	0.14	0.09	0.11	0.11	0.15	0.15
Peak transmittance	0.89	0.32	0.13	0.19	0.21	0.29	0.12	0.10	0.07	0.07	0.08	0.10	0.09
Wavelength uncertainty	0.24	0.21	0.19	0.16	0.14	0.11	0.08	0.05	0.03	0.03	0.01	0.01	0.01
Wavelength repeatability	0.08	0.12	0.12	0.15	0.14	0.15	0.11	0.08	0.01	0.07	0.07	0.11	0.11
Temperature	0.03	0.03	0.03	0.03	0.03	0.00	0.03	0.01	0.02	0.00	0.00	0.02	0.02
OOB leakage	0.30	0.22	0.26	0.10	0.11	0.08	0.03	0.04	0.03	0.03	0.04	0.05	0.05
Irradiance measurement	0.11	0.11	0.11	0.14	0.14	0.11							
Distance measurement	0.04	0.04	0.04	0.09	0.09	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Repeatability	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Diffraction	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Aperture area	0.01												
Interreflections	0.26	0.14	0.10	0.10	0.11	0.11	0.03	0.02	0.02	0.02	0.01	0.01	0.01
Interpolation	0.57	0.27											
Combined standard uncertainty	1.34	0.87	0.72	0.68	0.68	0.54	0.35	0.33	0.32	0.32	0.32	0.34	0.34
Expanded uncertainty ($k=2$)	2.7	1.7	1.4	1.4	1.4	1.1	0.7	0.7	0.6	0.6	0.6	0.7	0.7

The interreflection induced uncertainty is estimated by using the measured reflectance values in the pass bands of the filters. The interpolation induced uncertainty component is larger in the near UV where the back-reflectance from the trap detector is higher.

The uncertainty components listed in Table 1 are comparably low. According to our experience, such uncertainties can only be obtained by using high-quality and stable, especially stacked UV, filters.

3. References

- [1] P. Kärhä, T. Kübarsepp, F. Manoochchri, P. Toivanen, R. Visuri, L. Ylianttila, K. Jokela, E. Ikonen, "Portable detector-based primary scale of spectral irradiance," *J. Geophys. Res.* **105**, 4803-4807 (2000).
- [2] T. Kübarsepp, P. Kärhä, F. Manoocheri, S. Nevas, L. Ylianttila, and E. Ikonen, "Spectral irradiance measurements of tungsten lamps with filter radiometers in the spectral range 290 nm to 900 nm," *Metrologia* **37**, 305-312 (2000).

**Appendix 3.3 Evaluation of the uncertainty budget for the calibration of detectors
(extracted from the technical protocol of Key Comparison CCPR-K2.c)**

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- 1) The uncertainty of measurement shall be estimated according to the *ISO Guide to the Expression of Uncertainty in Measurement*. As well as the value associated with the uncertainty, an indication as to the basis of the estimate should be given. The coverage factor for the reported uncertainty should be stated.
- 2) The following uncertainty contributions should be considered:
 - a) Uncertainty associated with the primary reference used (for a given wavelength range covered by the primary reference) laser- or monochromator-based cryogenic radiometer, or room temperature ESR, or calculable quantum detector, or any other system.
 - b) Uncertainty associated with the spectral interpolation and/or extrapolation if the primary reference does not cover each of the wavelengths used:
 - spectrally flat detector (departure from ideal behaviour, repeatability, etc.)
 - calculable models of the detectors to be calibrated.
 - Uncertainty associated with the transfer from the primary reference: wavelength dependence, alignment, temperature, polarisation state of the beam used, effects of beam divergence, non-uniformity, calibration of amplifiers and voltmeters.
 - Other additional parameters may be felt appropriate to include dependent on specific measurement facilities and these should be added with an appropriate explanation and/or reference.
- 3) In order to achieve optimum comparability, a list containing the principal influence parameters for calibration of spectral responsivity standards is given below. Table 1 reviews some of the main sources of uncertainty contributing to the uncertainty to be associated with the calibration of the KC transfer detectors, for four main types of primary references given as examples. For various reasons, the KC transfer detectors are usually not calibrated directly against the primary reference. It is therefore assumed in these examples that they will be calibrated against NMI working standards directly traceable to the primary reference.
- 4) The uncertainty budget stated include all the information and sources of uncertainty which are relevant to the applied type of primary reference and calibration procedures. In Table 1, a cross indicates that the component described is usually relevant to the primary reference given on top of the column.
- 5) It should be noted that since several parameters are wavelength dependent, the combined uncertainty must be calculated for each wavelength or for each wavelength range.

Table 1. Main sources of uncertainty contributing to the uncertainty to be associated with the calibration of detectors, for four main types of primary references (given as examples). A cross indicates that the component described is usually relevant to calibration procedures based on the primary reference given on top of the column.

Source of uncertainty	Mono-chromator based CR	Laser based CR	Room temp. ESR	Calculable QD	Other
Primary reference					?
Window transmittance		x			
Scattered and diffracted light	x	x			
Cavity absorptance	x	x	x		
Electrical power measurements	x	x	x	x	
Non-equivalence electrical / optical power	x	x	x	x	
Other ...					
Interpolation and / or extrapolation when the primary reference does not cover each of the wavelengths of interest					?
Spectrally flat detector (residual wavelength dependence, uniformity, stability, ...)		x		x	
Mathematical models		x		x	
Other ...					
Calibration of NMI reference detectors (internal transfer)					?
Uniformity	x	x	x	x	
Linearity	x	x	x	x	
Polarisation dependence	x	x	x	x	
Vignetting effects	x	x	x	x	
Repeatability (stability of source, alignment, ...)	x	x	x	x	
Electrical calibrations (amplifiers, voltmeters, ...)	x	x	x	x	
Temperature	x	x	x	x	
Wavelength calibration	x	x	x	x	
Bandwidth effects	x	x	x	x	
Stray light	x	x	x	x	
Other ...					
Calibration of KC transfer detectors					?
Repeatability (stability of source, alignment, ...)	x	x	x	x	
Temperature	x	x	x	x	
Wavelength calibration	x	x	x	x	
Bandwidth effects	x	x	x	x	
Stray light	x	x	x	x	
Other ...					
Combined standard uncertainty	x	x	x	x	x

Appendix 3.4 Uncertainty evaluation, UV monitoring of solar radiation

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1. Introduction

The sun is the most important source of ultraviolet radiation on Earth. Its intensity at European ground level is temporarily so high that it will influence human health but also terrestrial and aquatic ecosystems. Therefore solar UV has become an important parameter that has to be monitored and radiation hygienic assessed continuously.

In the very beginning of the 90's several institutions in Europe started monitoring solar UV radiation. Spectrally resolved long term measurements have been done mostly at single stations, for example at Reading (GB), Thessaloniki (Greece), Brussels (Belgium), Amsterdam (Netherlands) and Arctic but also within a network in Germany. Broadband measurements have been done mostly within networks established for example in Great Britain, Sweden, Austria, Greece and Norway

Apart from data management and public education policy one very important question still remains - the uncertainty of the measurement.

2. Uncertainty

According to the “guidelines for site quality control of UV monitoring” the uncertainty in UV data mainly gathered from the instrument and its operation, the absolute reference and the site surroundings.

Contributions to the measurement uncertainty come from components in two categories, the instrument itself and the calibration. In general, the component calibration is very important. Most of the problems were described in the first chapter. This chapter will cover especially the parameters that will determine the uncertainty of solar UV measurements.

A. Radiation calibration

In solar UV radiometry 1000 W halogen lamps are usually used as the calibration light source. Beside uncertainties stated in the certificates of reference standards ageing, and operating of standard lamps the characteristics of the spectroradiometer will influence the irradiance calibration. Details in Chapter 1.

B. Cosine error

Due to the definition of the physical quantity “irradiance” the diffusor should have an “ideal” angular irradiance responsivity (cosine response) to measure the global spectral irradiance incident on a horizontal surface: a responsivity proportional to the cosine of the angle between the normal of the diffusor and the direction of incidence. Many diffusors used in UV spectroradiometers exhibit deviations from the ideal cosine of more than 10 % at $\alpha = 60^\circ$ and even greater with increasing α . Therefore the cosine error is one of the most important sources of error in solar spectroradiometry.

C. Spectral resolution

The slit function results in a systematic over-representation of the true irradiance at short wavelengths. In this range the sharp increase in irradiance (up to 5 orders of magnitude within 20 nm) leads to a significant contribution of radiation that comes from wavelengths longer than the designated wavelength. Typical bandwidths of current UV spectroradiometers are between 0,3 and 2,0 nm FWHM (full width at half maximum). For biologically weighted (e.g. erythemal) measurements the spectral resolution influences the results of ca. 1 to 2 % spectral irradiance.

D. Wavelength misalignment

Normal calibration procedure of wavelength is a comparison of measured and actual line positions of a mercury lamp at short wavelengths. Because of nonlinearities in the wavelength drive, deviations from the “true” values have to be within $\pm 0,3$ nm for the whole wavelength range. That implies for the measurements of biologically weighted irradiance an uncertainty of ± 2 %.

E. Stability

To reach reliable results and to monitor long term trends in solar UV irradiance radiometers must work with high stability. Especially the parameters temperature, high voltage of the photomultiplier, and the wavelength must be kept stable. Auxiliary lamps and Fraunhofer lines are helpful.

F. Nonlinearity

The photon current density of a radiometer should be proportional to the incident flux. In solar UV measurements in the UV A range the solar signal is of 2 – 3 orders higher than the calibration lamp signal, but in the UV B range 3 orders lower than the lamp signal.

G. Stray light

Stray light can be described as light that is not supposed to be transmitted to the detector but somehow reaches it after all. It is the result of scattering off the optical elements (gratings, mirrors, walls, etc.) within the monochromator re-entrered spectra, etc. For best stray light performance holographic gratings should be used. Additional, double monochromators with such gratings reduce stray light to values of 10^{-8} and allow reliable measurements below about 300 nm (depending on solar zenith angle).

Table 1. Total budget (at 295 nm, at higher wavelengths the error will be smaller, mostly because of smaller errors in wavelength setting).

Radiometric calibration (responsivity)	2 – 4 %
Radiometric linearity	1 %
Angular responsivity	2 – 10 %
Wavelength setting (repeatability)	8 %
Bandwidth	1 %
Temperature	1 %
Stray light	1 %
Other	1 %
Total (rms)	9 – 14 %

3. Activities of WG 2 within the UV thematic network project

A. Workshop 1

At the first meeting in Helsinki contributions came from the participants concerning the subjects instrument, entrance optics, calibration lamp, measurement campaign and quality control.

1) Instruments

A high precision instrument measuring solar UV is recommended to have the following specifications: double monochromator with holographic gratings and a bandwidth of ≤ 1 nm, is temperature controlled within $\pm 0,5^{\circ}\text{C}$, has a wavelength repeatability better than 0,05 nm, a stray light rejection better than 10^{-8} , and a dynamic range of 6 decades.

Instrument Systems introduced a fast scanning spectroradiometer (SRM), that can measure 20 – 50 times faster than existing commercial units. From 280 – 320 nm and at 1 nm bandwidth the minimum detectable irradiance is $1 \mu\text{W}/\text{m}^2$ within 5 seconds.

Long-term field measurements under extreme climatic and logistical conditions like Antarctica require a specialised instrument. The Alfred Wegener Institute for Polar and Marine Research (AWI) developed a non-scanning multi-channel detector system based on a Bentham DM 150 double monochromator. 32 channels working in a photon counting mode. To handle the stray light problem due to a broad centre slit, a steep interference filter with transmission maximum at 289 nm cuts 3 orders of magnitudes in dynamic. The complete instrument was presented on the workshop.

2) Entrance optics

The angular response of diffusors used with spectroradiometers for measurements of solar UV irradiance is generally not in good agreement with the ideal cosine response. Although a correction procedure may reduce the misleading effect of the cosine error, this can not be done satisfactory for all atmospheric conditions, i.e. broken cloudiness.

The Aristotle University referred of an effective cosine correction of global spectral

measurements obtained by Brewer spectroradiometers. The various stages of the methodology were described together with the uncertainties.

The Lichttechnisches Institut of the University of Karlsruhe presented a new developed reflective optic with a specially treated PTFE plate. The optic showed better results than existing ones.

Based on a recent development of a new type of Teflon diffusors in New Zealand, Blumthaler (University of Innsbruck) improved this diffusor by optimising the dimensions of the Teflon calotte. With a deviation of smaller $\pm 3\%$ for angles up to 75° global irradiance measurements are allowed without any additional cosine error correction procedure.

3) Calibration lamp

The uncertainty of calibration causes the most fundamental limitation for the accuracy of solar UV measurements. However, even the best lamps available are not stable enough, to match the increasing requirements due to the progress of the measuring technique. Especially the long-term stability in the UV-B region has to be improved.

The firm OMTec in Braunschweig introduced a stabilised transfer standard system for spectral irradiance. The new transfer standard system consists of a controlling unit including power supply and a lamp-detector-unit. The main features are the long time stability of more than 500 hours without re-calibration.

Because of the expense in time and personal the calibration procedure in the BfS/UBA UV monitoring network is only carried out in periods of about three months. To make a monitoring of short term changes in system sensitivity feasible an automatic working auxiliary lamp unit was developed. The mechanics of the unit is based on a modified wet-only precipitation sampler regularly used in air pollution monitoring. UV radiation is produced by a 35 W halogen lamp. Every night 5 spectra are registered. Until now the test of this system shows an overall variability of about $\pm 5\%$.

4) Measurements

Beside the discussions of hard- and software the exchange of experiences in measuring sUV (solar UV) is also of great interest. There are not so much institutions that measure sUV in Europe. So, this network gives a good support in data management.

In Ny-Ålesund (Norway) sUV is measured by the AWI since spring 1996. Additional from summer 1997 a spectroradiometer (Bentham DM150) and a portable LICOR 1800UW underwater spectroradiometer is in operation by the Norwegian Polar Institute. Permanent and campaign based measurements of sUV are performed to quantify the changing UV environment in the Arctic and to assess possible biological effects of increased levels of UV on marine terrestrial and freshwater ecosystems

5) Quality control and assessment

For the successful measurement of sUV standard methods of estimating the uncertainty associated with measurements and information about the correct interpretation and use of the data are needed. So, after establishing measuring sites by starting monitoring, this topic

became of increasing importance.

Results of a laboratory campaign for comparing devices that are used in measuring the current through a calibration lamp and comparing the secondary standard lamps of home laboratories were presented. Within this Nordic intercomparison a portable lamp unit circulated between monitoring sites in the according countries. The main result was that the agreement between spectral global UV measurements has improved during recent years. Additionally the use of lamp measurements in correcting for differences in the irradiance scale could noticeably improve the agreement.

Exemplarily with the high accuracy measurements of spectral solar UV performed by the Fraunhofer Institute for atmospheric research (IFU) current needs for solar UV spectroradiometry were presented. Especially the co-ordination of solar UV has to be improved. A great help will be the scientific steering committee established by the WMO that should co-ordinate UV activities. The remaining technical difficulties in an improvement of calibration accuracy, faster spectroradiometer and development of detector based calibration should be solved in close co-operation with state laboratories and industry.

B. Workshop 2

At the 2. Workshop in Braunschweig contributions to the 2 topics lamps and QA/QC were presented.

1) Calibration lamp

At the Finnish Meteorological Institute (FMI) the advantages and disadvantages of high and low watt lamps were discussed. High watt lamps are claimed to be more subject to abrupt and unpredictable changes in their characteristics. In a study, a high wattage lamp had shown a change of several percent in the lamp voltage, a simultaneous change in the broadband UV A and UV B irradiance could be seen, but of insignificant magnitude. This indicates that generally accepted criteria for the assessment of the lamp stability are missing.

2) Quality control/assurance

The “Guidelines for site quality control of UV monitoring” recently published by the WMO were presented in short. The guidelines contain detailed methods of evaluation the uncertainty associated with the spectral measurements of sUV. Following the algorithms and figures provided in the guidelines will lead to a “typical” uncertainty, achieved by a transparent method and comparable amongst different instruments.

The quality assurance strategy of BfS/UBA UV monitoring network was presented. It is based on regular calibrations and control with a 1000 W working standard, a daily control with a likewise BfS-developed 35-W ancillary source. Wavelength sensitivity is registered by HG-line measurements and during operation by a single Fraunhofer line in every solar spectrum. Additionally, the reference station participates in intercomparisons with a mobile reference system.

C. Workshop 3

At the third meeting in London contributions came from the participants concerning the subjects instrument, calibration lamp and measurement campaign.

1) Instrument

The AWI presented a solar radiation simulator useful for research on phytoplankton, macroalgae and fish eggs under stable conditions. With a 400 W metallogen lamp, distinct filters, liquids and a diffusor a solar spectrum can be well simulated and varied in ozone content, clouds, aerosol or depth in water.

2) Calibration lamp

The FMI Institute in Helsinki introduced a comparison of 5 purchased calibration 1000 W DXW lamps from different laboratories. The preliminary results indicated larger differences than expected. The irradiance scales could differ by up to 10 % through the whole wavelength range. Therefore could it be of advantage having a calibration obtained from more than one laboratory.

3) Measurements

The surface radiation depends to a significant amount on the reflectance properties of the surface (albedo). The Norwegian Polar Institute presented observations of the spectral reflectance of snow covered surfaces at different stages of melting. The measurements were done with a portable spectroradiometer in the UV, VIS and NIR region.

D. Workshop 4

At the 4. meeting in Borås, Sweden contributions came from the participants concerning the subjects instrument, calibration lamp and measurement campaign.

1) Instrument

The multichannel spectroradiometer the Alfred Wegener Institute (AWI) introduced at the first meeting in Helsinki was optimised. With a decreased UVB detecting region a bandwidth of 1 nm could be achieved. With a new photodiode array in the UVA a higher spectral resolution could be achieved. These features allow a time resolution of up to 1 sec per spectrum. Therefore the instrument is suitable to measure under fast changing inhomogeneous cloud conditions. Since March 2000 this new system is working at the NDSC-Station in Ny-Ålesund (Norway).

2) Calibration lamp

STUK, Finland presented a study of ageing DXW lamps over 80 hours. The irradiance dropped about 4 % with a 1-% difference between lower and higher wavelengths. The emissivity was stable during the burning time. The spectral changes were due to reduced filament temperature of 8 K during the 80-h burn.

3) Measurements

This winter scientists from Europe and USA measured dramatic less ozone in the higher atmosphere of the North Pole, less than winters before. Due to meridional circulation this will soon influence the ozone layer in Northern Europe, stronger than before combined with higher solar UV exposure.

The solar monitoring network of BfS/UBA that is measuring continuously and spectrally resolved solar UV irradiation in Munich, Frankfurt, in the southern black forest and at the Baltic sea and in collaboration with 5 more stations from different institutions had not observed an expected trend in increasing UV exposure. This is probably due to significant changes in the yearly meteorological conditions. Nevertheless there are many days in summer, few in spring, with erythemal weighted UV doses of 250 J/m²/30 min round high noon. That means a high UV level, radiation protection is necessary.

4. The future

A lot is done. We are now in the situation, that in the next few years climatologic maps of UV can be generated. With statistical analysis it should be shown, in which wavelength range, a trend of UV radiation would first become visible.

On the way to minimise uncertainties, some effort is to be done. Ancillary detection is needed and possible correlation with UV data looked for. Existing models have to be optimised to calculate numerical uncertainties of measured data.

From a radiation hygienic point, measurements with horizontally orientated entrance optics are not optimal because the worst case is not covered. Therefore optimal diffusor geometry has to be investigated, for example a sun following optic or a 2π detector.

5. Literature

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