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ADVANCES IN TRACEABILITY OF SOLAR ULTRAVIOLET RADIATION MEASUREMENTS

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ACADEMIC DISSERTATION
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Keywords Solar ultraviolet radiation, UV radiometry, UV metrology, calibration, traceability, quality control (QC), quality assurance (QA)

Abstract

Measurements of solar ultraviolet radiation (UVR) at STUK commenced in 1989, five years after the alarming observation of the ozone depletion in the Antarctic and in association with the establishment of the solar UV monitoring network of the Finnish Meteorological Institute. It was soon realised that the instrumentation for solar UVR measurements was far from adequate for the challenging task of measuring the solar UV spectrum. In addition, the intercomparison of lamps used as secondary standards of UV irradiance between the National Standard Laboratories revealed significant discrepancies.

In the course of this study, a national lamp-based scale for UV irradiance was established by STUK and subsequently was confirmed with the detector-based scale of the Helsinki University of Technology (HUT). Methods for (i) radiometric testing, (ii) calibration and (iii) data correction were developed for solar UV spectroradiometers and for broadband erythemally weighted (EW) solar UV radiometers.

A common opinion in the early 1990s was that EW radiometers were not good enough for solar UV monitoring; spectroradiometers or multi-channel narrow band radiometers were seen as the only option for reliable solar UV radiometry. Later on, several intercomparisons revealed that, without stringent methods of quality control (QC) and quality assurance (QA), even high precision spectroradiometers easily yield UV data erroneous by 20% or more. The reliability of the spectroradiometric solar UVR measurements made by STUK was verified in the Nordic solar UV radiometer intercomparisons in 1993 and 1996 and in the largest European intercomparison of solar UV spectroradiometers in 1997.

At STUK, it was considered that the low cost and easy-to-operate EW radiometers also had a role in solar UV monitoring. After developing the calibration methods for EW radiometers and gaining experience in testing of 16

EW radiometers, STUK organised the first international intercomparison of broadband EW radiometers in 1995 in cooperation with the University of Innsbruck and with support from the World Meteorological Organization. Twenty instruments from networks in 16 countries were characterised and calibrated. As a result, it became possible to trace calibrations of about 100 EW radiometers around the globe to the same origin. This is still the most comprehensive investigation of the performance of EW radiometers. It was concluded that EW radiometers may yield reliable UV data with uncertainties comparable to those of spectroradiometric measurements so long as stringent QC and QA methods are applied.

During this study, (i) the uncertainty of the UV working standards of STUK was improved from ca. 20% and 5% down to 4.1% and 1.6% at wavelengths of 250 nm and 350 nm, respectively, (ii) the uncertainty of spectroradiometric solar UVR measurements was decreased from ca. 20% down to 5.6% and (iii) the uncertainty of the spectroradiometric calibration of the temperature-stabilised EW radiometers in solar radiation was decreased from ca. 11% to 7.8%.

LESZCZYNSKI, Kirsti. Auringon ultraviolettimittausten jäljitettävyysketjun parantaminen. STUK-A189, Helsinki 2002, 78 s. + liitt. 84 s.

Avainsanat Auringon ultraviolettisäteily, UV-radiometria, UV-metrologia, kalibrointi, jäljitettävyys, laadunvalvonta, laadunvarmistus

Yhteenveto

Säteilyturvakeskus (STUK) aloitti auringon ultraviolettisäteilyn (UV-säteilyn) mittaukset Ilmatieteen laitoksen UV-monitorointiverkoston perustamisen yhteydessä vuonna 1989, viisi vuotta Etelämantereen otsoniohentuman havaitsemisen jälkeen. Pian huomattiin, että mittalaitteet eivät olleet riittävän tarkkoja täyttääkseen auringon UV-spektrin mittaamisen asettamat haasteet. Lisäksi sekundäärimittanormaaleina käytettävien lamppujen kansallisten mittanormaalilaboratorioiden väliset vertailumittaukset osoittivat merkittäviä eroja UV-alueella

Tämän tutkimuksen aikana STUK perusti Suomeen lamppupohjaisen UV-irradianssin referenssiasteikon, jonka Teknillisen korkeakoulun detektoripohjainen referenssiasteikko myöhemmin varmensi. STUKissa kehitettiin menetelmät spektroradiometrien ja laajakaistaisten eryteemapainotettujen mittareiden (EW-mittareiden, engl. erythemally weighted) (1) testaamiseen, (2) kalibrointiin ja (3) tulosten korjaamiseen.

1990-luvun alkupuolella vallitsi yleinen mielipide, että EW-radiometrit eivät olleet riittävän hyviä auringon UV-säteilyn monitorointiin; ainoina luotettavina UV-mittareina pidettiin joko spekroradiometreja tai kapeakaistaisia monikanavaradiometreja. Myöhemmin useat mittarivertailut paljastivat, että ilman tiukkoja laadunvalvonta- ja -varmistusmenetelmiä jopa tarkkuusspektroradiometreilla mitatut UV-tulokset saattoivat poiketa vertailuarvoista 20 prosenttia tai jopa enemmän. STUKin spektroradiometristen auringon UV-säteilyn mittausten luotettavuus varmennettiin auringon UV-radiometrien pohjoismaisissa mittarivertailuissa vuosina 1993 ja 1996 sekä laajimmassa eurooppalaisessa auringon UV-spektroradiometrien vertailussa vuonna 1997.

Säteilyturvakeskuksen näkemys oli kuitenkin se, että halvoilla ja helppokäyttöisillä EW-radiometreilla oli oma asemansa auringon UV-

monitoroinnissa. Kun EW-radiometrien kalibrointimenetelmät oli kehitetty ja 16 radiometria oli testattu, järjestettiin STUKissa vuonna 1995 ensimmäinen kansainvälinen EW-radiometrien vertailu. Vertailu toteutettiin yhteistyössä Innsbruckin yliopiston kanssa ja World Meteorological Organizationin tuella. Vertailussa testattiin ja kalibroitiin 20 mittaria 16 maasta. Tuloksena oli mahdollisuus jäljittää noin 100 EW-radiometrin kalibroinnit samaan alkuperään. Tähän päivään mennessä se on kattavin EW-radiometrien vertailu. Johtopäätös oli, että käytettäessä tiukkoja laadunvalvonta- ja varmistusmenetelmiä EW-radiometrit voivat tuottaa luotettavia UV-mittaustuloksia, joiden epävarmuus on verrattavissa spektroradiometri-mittauksiin.

Tämän tutkimuksen aikana (1) UV-irradianssin työnormaalien epävarmuus STUKissa parani noin 20 prosentista 4,1 prosenttiin aallonpituudella 250 nm ja viidestä prosentista 1,6 prosenttiin aallonpituudella 350 nm, (2) spektro-radiometristen auringon UV-säteilymittausten epävarmuus pieneni noin 20 prosentista 5,6 prosenttiin ja (3) auringon säteilyssä tapahtuvan spektroradiometrisen lämpötilastabiloitujen EW-radiometrien kalibroinnin epävarmuus parani noin 11 prosentista 7,8 prosenttiin.

Contents

List of publications

This dissertation consists of the present summary and the following publications, which are referred to in the text as Publs. I-VI.

I Leszczynski K., K. Jokela, R. Visuri, L. Huurto, J. Simola, T. Koskela, P. Taalas and A. Aarva, *Performance tests of two Robertson-Berger type UV meters Solar Light model 500 and 501.* In: K. Stamnes (Ed.), Proc. international symposium on high latitude optics, Tromsø, Norway, 28 June - 2 July 1993, SPIE Proc. **2049**, 162-173, 1993.

II Leszczynski K., K. Jokela, R. Visuri and L. Ylianttila, Calibration of the broadband radiometers of the Finnish solar UV monitoring network. *Metrologia* **32**, 701-704, 1995/1996.

III Leszczynski K., *UV monitoring in Finland: past, present and future*. Invited review article in: B. L. Diffey (Ed.), Measurement & trends of terrestrial UVB radiation in Europe, Organizzazione Editoriale Medico Farmaceutica, Milan, 55-71, 1996.

IV Leszczynski K., *Quality control of broadband solar UV measurements.* Invited position paper presented in the WMO-UMAP workshop on broadband UV radiometers, Garmisch-Partenkirchen, Germany, 22-23 April, 1996. In: World Meteorological Organization, Global Atmosphere Watch Report No. 120, WMO TD No. 894, 43-59, 1998.

V Leszczynski K., K. Jokela, L. Ylianttila, R. Visuri and M. Blumthaler, Erythemally weighted radiometers in solar UV monitoring: results from the WMO/STUK intercomparison. *Photochem. Photobiol.* **67**, 212-221, 1998.

VI Leszczynski K., L. Ylianttila and R. Visuri, *WMO/STUK '95 intercomparison of broadband UV radiometers: a small-scale follow-up study in 1999*. Accepted for publication in the Global Atmosphere Watch Report Series of World Meteorological Organization.

Author's contribution

The author has taken an active part in the whole project of establishing and developing the UVR monitoring facilities at STUK. The first contribution concerned the improvement of the accuracy of the basic calibration of the instrumentation used in the measurements described in this dissertation. In characterisation of the spectroradiometer Optronic 742 used at STUK for solar ultraviolet radiation measurements, the author played an active role in the actual measurements of temperature sensitivity, slit function and cosine response *[Publs. I, III]*. She contributed to the experimental determination of temperature sensitivity and to the measurement of cosine and spectral responsivities of the erythemally weighted (EW) broadband meters *[Publs. I-IV]*.

The most important contribution of the author was organising and taking an active part in the first international intercomparison of EW radiometers *[Publ. V]*. This project yielded crucial information necessary for improving the accuracy and comparability of the worldwide solar UVR measurements. The author also played a significant role in developing the methods for quality control and quality assurance of EW solar ultraviolet radiation measurements *[Publ. IV]*.

The author has prepared all manuscripts included in this dissertation. All of the publications are the result of group efforts of the contributing scientists.

Nomenclature

List of symbols

δ	Dirac delta function
θ, θ_z	solar zenith angle
θ_o	solar elevation angle
λ, λ_o	wavelength
$\Delta\lambda$	bandwidth, spectral range
ϕ	azimuthal angle
Φ	radiant flux
ω	solid angle
A	area
$A(\theta)$	actual cosine response
$B(\lambda),B_\lambda$	biological action spectrum
$C(\theta)$	relative cosine response
E	irradiance
$E(\lambda),E_\lambda$	spectral irradiance
E_{eff}	(biologically) effective irradiance
E_{dif}	diffuse irradiance component of the solar UVR
E_{dir}	direct irradiance component of the solar UVR
H_{eff}	(biologically) effective exposure
k	coverage factor
K	calibration factor
L	radiance
L_λ	spectral radiance
L_{dir}	direct solar radiance component from the Sun
L_{dif}	diffuse solar radiance component scattered from the sky
R_Φ	instrument responsivity
$r(\lambda)$	spectral responsivity
S	output signal of an instrument
t	time
x	dimensional coordinate
y	dimensional coordinate

List of abbreviations

ATI	University of Innsbruck
BIPM	Bureau International des Poids et Mesures
CCPR	Comité Consultatif de Photometrie et Radiometrie of the Comité International des Poids et Mesures
CF	Calibration Factor
CF_{AVE}	Average value of CFs of solar elevations higher than 35°
CIE	Commission Internationale de l'Eclairage
CIPM	Comité International des Poids et Mesures
DNA	DeoxyriboNucleic Acid
DQO	Data Quality Objectives
DXW	Double-ended double-coiled (tungsten–halogen lamp)
DU	Dobson Unit
EA	European Accreditation
EW	Erythemally Weighted
FEL	Single-ended double-coiled (tungsten–halogen lamp)
FMI	Finnish Meteorological Institute
FWHM	Full Width at Half Maximum
GE	General Electric, U.S.A.
GO	Gigahertz-Optik, Germany
HUT	Helsinki University of Technology
MED	Minimum Erythemal Dose
NIST	National Institute of Standards and Technology, U.S.A.
NOGIC	Nordic Ozone Group InterComparison
NPL	National Physical Laboratory, U.K.
NSL	National Standards Laboratory
OL	Optronic Laboratories, Inc., U.S.A.
PTB	Physikalisch-Technische Bundesanstalt, Germany
QA	Quality Assurance
QC	Quality Control
R-B	Robertson-Berger
SED	Standard Erythema Dose
SI	International System of Units
SL	Solar Light Co., U.S.A.
SNR	Signal-to-Noise Ratio
SRF	Spectral Responsivity Function
STUK	Radiation and Nuclear Safety Authority, Helsinki, Finland
UMAP	UV Monitoring and Assessment Panel

UNEP	United Nations Environment Programme
UTH	University of Thessaloniki
UV	Ultraviolet
UV-A	Ultraviolet Radiation from 320 to 400 nm
UV-B	Ultraviolet Radiation from 280 to 320 nm
UV-C	Ultraviolet Radiation from 100 to 280 nm
UVR	Ultraviolet Radiation
WMO	World Meteorological Organization
YES	Yankee Environmental Systems, Inc., U.S.A.

1 Introduction

The history of solar ultraviolet radiation (UVR) monitoring is relatively short, less than three decades. If we exclude the UVR monitoring efforts carried out in the late 1920s in Finland by Lunelund *[1929, 1944]* and in the 1960s in Switzerland by Bener *[1960, 1963, 1964, 1972]*, the year 1974 can be considered as the starting point for solar UVR monitoring. In that year, the first solar UVR monitoring network of 25 broadband UV radiometers was deployed in the United States to establish the North American UV climatology *[Scotto et al. 1988]*. In addition to the U.S. network, twelve other broadband radiometers were taken into use around the world at the same time *[Weatherhead and Webb 1997]*. However, it was only the discovery of springtime depletions of the ozone layer, up to 70%, over Antarctica in the 1980s *[Farman et al. 1985]*, followed by observations of episodic springtime ozone depletions in arctic regions *[Taalas et al. 1996]*, that finally alerted the scientific community to the necessity of extensive ground-based solar UVR monitoring.

Decrease in stratospheric ozone leads to an increase in UV irradiance at the Earth's surface. It has been estimated that, at northern midlatitudes (25-60ºN), the ozone abundances for 1994-97 averaged about 4% below the 1979 values, and since 1994 the total column ozone has remained more or less constant in that region. The observed linear downward trends between 1979 and 1991 were 4.0%/decade in the winter and spring and 1.8%/decade in the summer and fall *[WMO 1999]*. Based on measured and calculated data, the increase in spectral UV irradiance at *e.g.* 310 nm due to an ozone reduction of 1% relative to 300 Dobson Units (DU)[1] is 1 to 2% depending on the solar elevation angle. It has been estimated that erythemally weighted solar irradiance increases by ca. 1.4% for a 1% decrease of total ozone *[WMO 1999]*. It is evident from these figures that the requirement for long-term stability of UV radiometers must be stringent if UV trends due to ozone depletion are to be detected. The assessment of UV trends is further complicated by the variability of cloud cover, tropospheric pollution and aerosol content of the atmosphere. Ground-based measurements of solar UVR are essential for confirming the actual changes in UV levels associated with the changes in stratospheric ozone

[1] Dobson Units are used to describe the total amount of stratospheric ozone in an overhead column of the atmosphere. Dobson Units express how thick the layer of ozone would be if it were compressed into one layer at standard temperature and pressure (0°C and 101.3 kPa). Every 1 mm thickness of the layer is equivalent to 100 DU. In Finland, the annual variation of the long-term mean values of ozone content is approximately 270 to 410 DU.

concentration when the ability for accurate calculations of UVR is still limited *[UNEP 1998, WMO 1999, Seckmeyer et al. 2001]*.

Accurate trend-evaluation of UV levels on the Earth's surface is crucial because of the adverse effects caused of increased UV levels on human health, animals, plants, micro-organisms, materials and air quality. The increase in erythemal UVR associated with stratospheric ozone loss is known to increase incidence and severity of (i) skin cancer, (ii) cataract and (iii) acute photokeratitis (snowblindness) and to affect the immune system *[UNEP 1998]*.

Radiometers used for solar UVR measurements can be divided into three categories on the basis of their bandwidths. Spectroradiometers, the most accurate solar UV radiometers, have bandwidths varying from approximately 0.5 to 1.5 nm. The so-called multi-channel radiometers have typically two to eight measuring bands in the UV, with the bandwidths varying from 2 to 20 nm. Erythemally weighted (EW) broadband radiometers have a spectral responsivity covering the region from ca. 260 to 380 nm and roughly following the erythemal effectiveness *[McKinlay and Diffey 1987]* of the UVR.

The choice of UV monitoring instrumentation depends on the nature of the problem to be addressed *[Leszczynski 1995, 1999]*. Spectral measurements of high precision are required for detecting UV trends associated with the depletion of stratospheric ozone and for providing data for evaluating radiative transfer models. On the other hand, relatively simple broadband EW radiometers, which are low-cost and easy to operate, are a good choice for the establishment of global networks of numerous monitoring sites for the purposes of UV epidemiology and ecological studies.

There were only some tens of solar UV-monitoring sites in 1990, the instrumentation being spectral and broadband radiometers. The multi-channel instruments were deployed later in the decade. During the first half of the nineties, the numbers of solar UV radiometers increased rapidly in response to concern over depletions in the ozone layer. In 1997, Weatherhead and Webb *[1997]* estimated that the number of solar UV monitoring radiometers around the world was over 250. Today, the number of meters is significantly higher. Based on information from the manufacturers[2] in October 2002, it can be estimated that the numbers of UV monitoring spectroradiometers and multi-channel and broadband radiometers are about 350, 200 and 1200, respectively, for a total of 1750 radiometers. The problem is that in most cases the data yielded by these radiometers are not really comparable; this is due to diversity in the instrumentation, but also in the calibration and measurement procedures.

The first intercomparisons of solar UV spectroradiometers indicated discrepancies of tens of percent in solar measurements and even in calibration lamp measurements *[Josefsson 1991, Gardiner and Kirsch 1992]*. During the history of repeated intercomparisons *[Gardiner and Kirsch 1993, 1995, Koskela 1994, Seckmeyer et al. 1994, Kjeldstad et al. 1997, Thompson et al. 1997, Early et al. 1998a,b, Bais et al. 2001]*, significant improvements have been achieved, the best agreement having been within 5 to 10% *[Gardiner and Kirsch 1995, 1998, Webb 2000, Bais et al. 2001]*.

The main reasons for the non-coherent results from the early intercomparisons of solar UV spectroradiometers were non-ideal cosine responses, errors in wavelength scales, wide variations of slit functions and temperature sensitivity related errors. For example, at zenith angles greater than 60° the deviation from the cosine response was typically more than 10%. Shifts of wavelength scales as great as 1 to 4 nm were reported *[Gardiner and Kirsch 1992],* and a shift of 0.25 nm already produces an error of approximately 7% in the CIE-weighted solar UV irradiance. A difference of ± 5 °C between the calibration and measurement temperatures of the optics head of a spectroradiometer may cause an error of ± 5% in the CIE-weighted solar UV irradiance *[Publ. III]*.

Currently, if the actual operation of the radiometers is excluded, the most significant sources of uncertainty[3] in spectroradiometric solar UVR measurements are non-ideal cosine response (± 2%), inaccuracy of the wavelength scale (± 3%) and non-ideal slit function (± 1%). After deployment of the new diffuser designs *[Bernhard and Seckmeyer 1997]* and the application of

[2] Information was obtained on the following instruments: Bentham spectroradiometers, Biospherical multi-channel instruments and spectroradiometers, Brewer and Optronic spectroradiometers, Scintec and Solar Light EW radiometers, Yankee Environmental Systems (YES) EW and multi-channel radiometers and NILU-UV multi-channel radiometers.

[3] Unless otherwise stated, the uncertainties throughout this dissertation are given as expanded uncertainties obtained by multiplying the combined standard uncertainty by a coverage factor k=2 yielding a confidence level of approximately 95% *[ISO 1995]*.

numerical correction for the residual cosine error *[Publs. I-V, Seckmeyer and Bernhard 1993, Leszczynski et al. 1997, Bais et al. 1998]*, and after improvement of the wavelength calibration by applying a method using a suitable high-resolution extraterrestrial spectrum as reference *[Slaper et al. 1995],* the uncertainty of the absolute calibration (± 2%) has become one of the most significant sources of uncertainty in spectroradiometric solar UVR measurements with temperature-stabilised instruments *[Jokela et al. 2000]*. The uncertainties indicated represent state-of-the-art values as of 2002 for solar UVR measurements above 300 nm.

Uncertainties of the reference standards used to disseminate the scales of spectral irradiance in the UV region as specified by the National Standards Laboratories (NSL) vary from 1.0 to 4.0% and intercomparisons of these standards indicate even greater discrepancies *[Walker et al. 1991, CCPR 1997]*. Development of a detector-based traceability chain for solar UVR measurements promises to alleviate the serious accuracy and instability problems associated with the transfer of calibration from the primary standards to the user by means of unstable tungsten-halogen lamps *[Kärhä et al. 1996, 2000, 2002, Jokela et al. 2000]*.

The current ultimate limit for the absolute uncertainty of solar UVR measurements with the highest precision spectroradiometers is ca. ± 5-6% *[WMO 1999, Bernhard and Seckmeyer 1999]*. An uncertainty level below ± 10% can be achieved only with thoroughly characterised spectroradiometers under strict quality control (QC) and quality assurance (QA) programmes[4].

As compared with spectroradiometric solar UVR measurements, much less effort has been directed to improving the quality and comparability of broadband measurements. The first broadband radiometer designed to

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[4]According to the definitions by WMO, **QC** is part of **QA.**
QA consists of the following three elements *[Webb et al. 2002]*:
1) Definition of data quality objectives (DQOs). The DQOs are derived from the intended use of the data and also reflect the technological constraints – if any.
2) **QC** activity is the responsibility of the data producer and requires adherence to good laboratory practice as well as all measures that directly or indirectly influence data quality. The data producer is held responsible for following the standard operating procedures. The data producer is primary guardian of the data quality.
3) Quality assessment. The quality assessment means an "external" review of data quality by a group or organisation that is independent of the data producer. It ensures that all quality related measures have indeed been carried out by the data producer. Upon careful review and audits, the quality of data is certified.

measure UVR with a spectral responsivity approximating the erythema action spectrum, the Robertson-Berger (R-B) radiometer, was introduced in the mid-seventies *[Robertson 1972, Berger 1976].* However, except for a study of the absolute radiant energy of a single R-B meter *[DeLuisi and Harris 1983]* and measurements of the temperature sensitivity of another R-B meter *[Blumthaler and Ambach 1986]*, QC/QA efforts for EW meters were not pursued till the late 1980s. Indeed, because of inadequate QC/QA methods, the R-B solar UV data from the first solar UV network in the United States failed to confirm the expected increase in UVR associated with the observed depletion of the column ozone over the mid-latitudes of the Northern Hemisphere *[Scotto et al. 1985, Frederick 1992, Frederick and Weatherhead 1992, Kennedy and Sharp 1992, DeLuisi et al. 1992].*

In 1991, when justification and criteria for the future monitoring of UVR were discussed in the UV-B measurements workshop in the United States, it was concluded that the R-B meter network should have been kept in operation only until network spectroradiometers were in operation *[Gibson 1991].* However, the 1992 UV-B workshop concluded that the broadband instruments might be the only alternative for establishing a solar UV network *[Gibson 1992].* In the early 1990s, Johnsen and Moan *[1991]* reported on the temperature sensitivity of a single R-B meter, Jokela et al. *[1991]* reported preliminary temperature sensitivity, angular and spectral responsivity and solar simulator based calibration data for five R-B meters, DeLuisi et al. *[1992]* published studies on spectral responsivities of seven R-B meters and Grainger et al. *[1993]* reported angular and spectral responsivities together with field calibration data for a single R-B meter. In their study, Grainger et al. introduced a method for correcting for the non-ideal angular response of the R-B meter.

The necessity of improving the quality of broadband solar UVR measurements was recognised at the Radiation and Nuclear Safety Authority (STUK), Helsinki, Finland in 1990, when testing of the EW radiometers was started in association with the establishment of the solar UV monitoring network *[Jokela et al. 1991, Publ. I, Leszczynski 1995, Leszczynski et al. 1996].* As part of that project, methods for radiometric tests and calibration of the broadband meters were developed *[Publs. I-III].*

The first international intercomparison of EW radiometers was arranged at STUK in 1995, in co-operation with the University of Innsbruck and with support from the World Meteorological Organization (WMO) *[Publ. V, Leszczynski et al. 1997].* By the end of 1998, more than 40 EW radiometers had been radiometrically characterised by STUK through measurement of the angular and spectral responsivities, and calibrated in solar radiation. It was concluded that, with well-characterised EW radiometers calibrated in solar radiation against a high precision spectroradiometer, an uncertainty of less than 15% could be achieved *[Publ. V]*.

In 1996, the WMO/UMAP (UV Monitoring and Assessment Panel) broadband UV radiometer workshop concluded that EW radiometers play an important role in UV-B measurements at the Earth's surface. Erythemally weighted meters were recognised as an option for trend detection and establishing the climatology of erythemally weighted UV irradiance *[WMO 1998]*.

In this dissertation, emphasis is put on solar UV metrology, and problems in calibration and traceability are discussed in depth. The methods introduced for QA and QC of EW solar UVR measurements are described in detail.

2 Aims and progress of the work

This dissertation describes and discusses the improvement of the accuracy and reliability of spectroradiometric and broadband EW solar UVR measurements over the past ten years. The improvement has been achieved through the development of stringent QC and QA methods, *i.e.* methods for instrument characterisation and calibration, and also for the correction and validation of the measured data.

The necessity of improving the quality of broadband solar UVR measurements was recognised at our laboratory in 1990, when testing of the EW radiometers began *[Publ. I]*. Since the traceability of EW measurements is based on using a spectroradiometer as a reference instrument, sources of error in spectroradiometric solar measurements were thoroughly assessed. STUK was one of the first laboratories in the world where numerical corrections were applied to compensate for the systematic sources of error in spectroradiometric solar UVR measurements *[Publs. I-III]*. Methods for (i) determining the angular and spectral responsivities and (ii) calibrating the EW meters were developed *[Publs. I-V]*. The first international intercomparison of EW radiometers was arranged at our laboratory in 1995 *[Publ. V]*. By 1999, our research group had calibrated and radiometrically characterised more than 40 EW radiometers worldwide.

The first study *[Publ. I]* was carried out in connection with the establishment of the three first sites of the solar UV monitoring network by the Finnish Meteorological Institute (FMI). The aim was to test the feasibility of EW meters for solar UV monitoring. Publ. I presents test results for six EW radiometers including cosine and spectral responsivities together with temperature coefficients for the four first meters, which were not temperature-stabilised. A method is introduced for the calibration of the EW meters in solar radiation against a spectroradiometer. Also, temperature sensitivity of the reference spectroradiometer is recognised as an error source. The calibration of the wavelength scale of the spectroradiometer is performed by measuring the 253.65 nm mercury line at the beginning of each solar spectrum. Publication I was internationally one of the first studies where a cosine correction was applied to spectroradiometric solar measurements. At this stage, however, only a single factor was used for the cosine correction, not an elevation–angle–dependent correction function. Absolute accuracy of the UV measurements at STUK was based on one 1000-W FEL-type[5] and two 200-W DXW-type[6] tungsten-halogen incandescent standard lamps from Optronic Laboratories, Inc., U.S., claimed to be traceable to National Institute of Standards and Technology (NIST), U.S.A., but without any certification. The main conclusions of Publ. I were that EW meters can be considered a feasible alternative for establishing global UV monitoring networks provided that each EW meter is thoroughly characterised and calibrated and that strict QA/QC methods are applied to all measurements.

The second paper *[Publ. II]* presents test results for nine temperature-stabilised EW meters. Calibration methods for the EW meters are further developed. When the calibration is made against CIE-weighted *[McKinlay and Diffey 1987]* solar spectra, systematic increase of the calibration factors (CFs) towards solar elevation angles below 35 degrees is observed, and the concept of an average calibration factor (CF_{AVE}) for solar elevations higher than 35 degrees is introduced. Significantly improved agreement of daily doses after applying CF_{AVE}s is demonstrated. The method for cosine correction of the spectroradiometric data is improved. Instead of a single factor, an elevation–angle–dependent correction is applied to the spectral data. Moreover, for the first time, the variability of cosine correction factors is reported for EW meters. The effect of the deviation of a typical spectral responsivity function of an EW meter from the ideal CIE action spectrum of erythema is analysed and graphically presented for varying ozone contents as a function of solar elevation angle. The uncertainty of the calibration of the reference spectroradiometer is improved by introducing a high accuracy shunt resistor and voltmeter to monitor the lamp current.

Publication III is a review article summarising all main findings during the development of the Finnish solar UVR monitoring network up until 1996. Methods applied in characterisation of solar UV radiometers (e.g. cosine and spectral responsivities, slit function, temperature sensitivity) are described in detail. The overall number of tested EW meters had by then increased to 36. Preliminary results from the WMO/STUK '95 intercomparison of EW radiometers are included. Cosine correction factors for nine EW meters and the reference spectroradiometer are presented as a function of solar elevation angle. Preliminary stability data for two FMI network instruments within the two first years of monitoring and for one instrument for three years are

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[5] FEL-type lamps are single-ended double-coiled tungsten–halogen lamps.

[6] DXW-type lamps are double-ended double-coiled tungsten–halogen lamps.

reported. Quality control of the calibration of the reference spectroradiometer had been improved by including monitoring of the voltage drop across the lamp during the calibration. The calibration chain was improved by purchasing a reference standard lamp for STUK directly from a primary standards laboratory, NIST. An uncertainty budget for solar UVR measurements is presented. The review also briefly summarises some UV exposure data in Finland associated with springtime ozone depletions and snow reflection based on model calculations and EW measurements.

The main contributions of publication IV, the position paper in the WMO report, are the recommendations for the calibration and QA/QC methods for EW solar UVR measurements supported by the preliminary results of the WMO/STUK intercomparison. Of these recommendations, the methods suggested for instrument characterisation and calibration of EW meters have since been implemented in the recommendations by WMO *[WMO 1998. Webb et al. 1998]*. Publication IV also reveals particular significant problems in traceability of solar UVR measurements. Discrepancies of up to 7% between the standard lamps from Optronic Laboratories, Inc. and NIST are reported, as well as temporary instability of several per cent of a NIST lamp. These findings were crucial in directing the QC efforts towards improving the traceability chain of the solar UVR measurements.

Publication V presents the final results of the first international intercomparison of EW radiometers arranged by STUK in 1995. Test and calibration data for 20 EW radiometers of six different types are reported. The results, *e.g.* variation of the average values of the calibration factors of the EW meters, CF_{AVE}s, from 0.87 to 1.75, indicated that either the manufacturer calibrations of the meters were no longer valid or that the calibration methods had not been compatible. The 20 EW meters tested belonged to various solar UV monitoring networks around the world. Hence, as a result of the WMO/STUK intercomparison, it became possible for the first time to trace calibrations of more than 100 EW radiometers to the same origin. In addition, publication V includes preliminary results from the Nordic intercomparison of solar UV radiometers in 1996, NOGIC '96, for five EW radiometers. The results allowed the conclusion that, with proper QA/QC methods, the accuracy of EW meters can be made comparable with that of many commonly used spectroradiometers.

The last paper, publication VI, reports the results of characterisation and calibration measurements repeated four years later for two EW meters included in the WMO/STUK '95 intercomparison. Publication VI concludes from the results that the EW meters seemed to exhibit reasonably good stability.

To summarise, the research presented in this dissertation has played a significant role on the national level by establishing the traceability chain for the UV monitoring data yielded by the solar UV monitoring network of the Finnish Meteorological Institute. On the international level, a major achievement was that, for the first time, the calibrations of more than 100 EW radiometers around the world could be traced to the same origin. A second achievement was that the methods suggested for the QC and QA of EW solar UV monitoring *[Publ. IV]* have been implemented in the recommendations of WMO aimed at improving the quality of broadband UV monitoring data.

3 Traceability of solar UVR measurements

Traceability requires that measurements are related to references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties *[ISO 1993]*. In solar UVR measurements, these requirements for traceability are often not met. Firstly, in many solar UV monitoring laboratories, the reference standard lamps are neither from national standards laboratories (NSLs) nor from accredited calibration laboratories or laboratories working in close cooperation with NSLs. These laboratories may claim traceability but without any certificate documenting the traceability to national standards, which realise the physical units of measurement according to the International System of Units (SI). Secondly, in solar UVR measurements, determining the sources of uncertainty requires considerable effort, and detailed uncertainty budgets are often not shown or have not been calculated. Further, even if the measurements are traceable to national standards, measurements based on different traceability chains may not be intercomparable due to discrepancies between these standards *[Walker et al. 1991, CCPR 1997]*. Moreover, even the reference standards from the NSLs and accredited laboratories have indicated values erroneous by 6 to 10% or even more *[SUSPEN 1998, Bernhard and Seckmeyer 1999]*. These findings are supported by the experience at STUK (see section 3.3).

3.1 Traceability chains

The absolute accuracy of spectroradiometric solar UVR measurements is most commonly based on the calibration of solar UV spectroradiometers against tungsten–halogen standard lamps traceable to primary standards maintained at NSLs such as NIST, NPL (National Physical Laboratory, U.K.), PTB (Physikalisch-Technische Bundesanstalt, Germany) and HUT.

At NIST, for example, the source-based scale for spectral irradiance was until recently derived from blackbody radiation by applying Planck's law to accurately measured temperature of the blackbody. The spectral irradiance scale was transferred to a set of four 1000-W tungsten–halogen primary working standards *[Walker et al. 1987]*, which were then used to calibrate the secondary standards supplied by NIST. The way of realising the NIST scale of spectral UV irradiance was changed in 2000. The new detector-based scale uses filter radiometers whose spectral irradiance responsivity is derived from the absolute high accuracy cryogenic radiometer and a high-temperature (~ 3000 K) blackbody. From the assignment of the radiance temperature using the filter radiometers, the spectral irradiance of a group of FEL lamps is determined. The agreement between the former source-based and the new detector-based scales is reported to be within combined uncertainties (k=2) of the measurements. In the UV region, the detector-based spectral scale results in the reduction of uncertainties by at least a factor of two *[Yoon et al. 2002]*.

In solar UV monitoring laboratories, a secondary standard from NSL is used to calibrate the working standards, 200-W or 1000-W DXW-type or FEL-type lamps, actually used for calibration of the solar UV spectroradiometers. As a second step, the spectroradiometer is used to transfer the calibration to the reference broadband EW radiometer in solar radiation, and as a final step the reference EW radiometer is circulated through the monitoring sites to calibrate the network radiometers *[Publ. IV, WMO 1998]*. The dissemination of the UV scale from the primary standard to the solar UV monitoring radiometers requires a minimum of three calibration steps, but commonly even six to eight steps are used. An example of a typical lamp-based traceability chain for solar UVR measurements is presented in Fig. 1.

The major problem with the conventional source-based calibration chain is the instability of the lamps. Ageing-related changes up to 3 to 4% per 100 h burn time in irradiance of 1000-W tungsten–halogen lamps have been reported. In addition, there occur abrupt short-term changes that may be even greater *[Sperling et al. 1996, Publ. IV, Jokela et al. 2000, Harrison et al. 2000]*. Harrison et al. *[2000]* reported also transportation-related changes in irradiance of over one in three lamps tested. According to Harrison et al. *[2000]*, the changes in the irradiance are caused by bulk movement of the filament or collapse of the filament windings, and may not always be apparent in changes of the voltage and current supplied to the lamp.

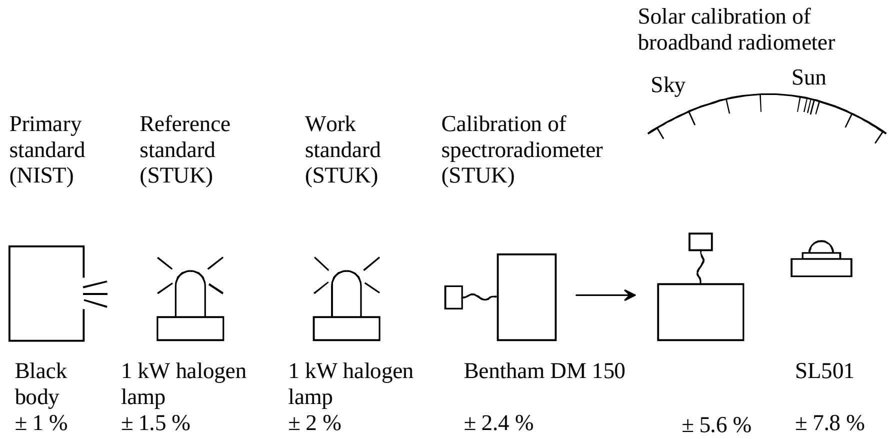

Figure 1. *Lamp-based calibration chain for solar UV radiometers established by STUK [Jokela et al. 2000]. The percentages are given as expanded uncertainties (k=2) updated to present state-of-the-art as of 2002.*

In view of the instabilities of the lamp standards, it has been recommended that each stage of the traceability chain should be based on a minimum suite of three lamps *[Webb et al. 1998]*. In addition, at least one of the standard lamps should be certified by an accredited calibration laboratory or by an NSL.

HUT has introduced a detector-based calibration method to overcome the problems caused by instabilities of lamps *[Kärhä et al. 1996, 2000, Kübarsepp et al. 2000]*. In this method, stable narrowband filter radiometers calibrated against an absolute cryogenic radiometer are used for the basic realisation of the scale from 280 to 400 nm and to transfer the scale to the standard lamps. The filter radiometer system is easily portable to laboratories where the lamps that need to be calibrated are located. This method allows the shortest possible traceability chain from NSL scales to field measurements.

Detector-based spectral irradiance scales have been developed also in NPL and PTB *[Hartree et al. 1995/96, Sperfeld et al. 1998, Woolliams et al. 2002]*. The need for developing better transfer standard sources in the UV region has been recognised by the CCPR, and improvement of existing sources through detector stabilisation has been suggested *[CCPR 1997]*.

3.2 Uncertainties of the secondary standards of UV irradiance

3.2.1 Lamps supplied by NSLs

The uncertainties of the spectral irradiance specified in the calibration certificates of the secondary standards issued by NSLs vary from 1.1 to 4% depending on the wavelength. However, results from the intercomparison of halogen lamp measurements between 12 NSLs in 1987 through 1990 indicated maximum differences of more than 4% in the UV range *[Walker et al. 1991]*, and results from the 1993-94 intercomparison between NIST, NPL and PTB revealed even larger differences (up to 8% at wavelengths longer than 300 nm) *[CCPR 1997]* (Fig. 2). In a 'small-scale' intercomparison carried out by HUT and STUK in 1998, the calibrations of lamps traceable to PTB, NIST and HUT agreed to within 1.5% *[Jokela et al. 2000, Kärhä et al. 2000]*. The latest CCPR intercomparison of spectral irradiance scales of 14 NSLs, the *CCPR-K1.a comparison,* commenced in 2001 and is still in progress *[BIPM 2002]*.

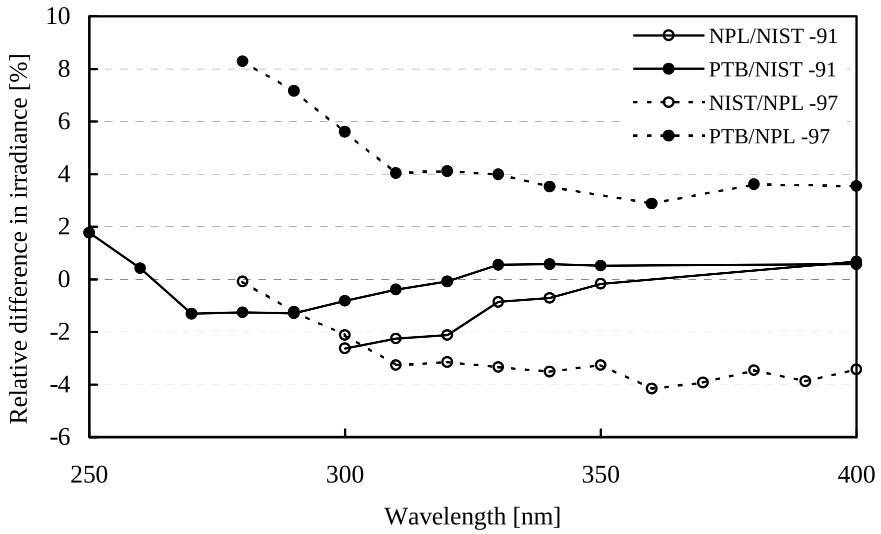

Figure 2. *Differences of spectral irradiance scales of NIST, NPL and PTB based on two lamp intercomparisons of NSLs [Walker et al. 1991, CCRP 1997].*

3.2.2 Lamps used by solar UV-monitoring laboratories

Some solar UV monitoring laboratories purchase their lamps directly from NSLs, but many use lamps from other lamp suppliers maintaining secondary standards. Owing to the increasing uncertainty along the calibration chain, the differences between the lamps from these suppliers are expected to be even greater than the differences between the lamps from NSLs. At STUK, a discrepancy of seven per cent was observed between a NIST lamp and a lamp purchased from Optronic Laboratories *[Leszczynski et al. 1996, Publ. IV]*.

Besides the intercomparisons arranged between NSLs, lamp intercomparisons have also been arranged between solar UV-monitoring laboratories *[Gardiner and Kirsch 1992, 1993, 1995, Leszczynski et al. 1994a, Johnsen et al. 1997, Thompson et al. 1997, Early et al. 1998a,b, SUSPEN 1998, Bais et al. 2001]*. During the first European intercomparison of UV spectroradiometers in 1991, deviations up to ± 20% were observed between the UV standards of the participants of *[Gardiner and Kirsch 1992]*. In the second intercomparison in 1992 the maximal deviation was reduced to below ± 10% *[Gardiner and Kirsch 1993]*. By the mid-nineties the agreement of the lamp standards of the UV monitoring laboratories was even better than could be expected in the light of results between the NSLs, typically within ± 3% *[Johnsen et al. 1997, SUSPEN 1998]*. This good agreement might be partly explained by the traceability of the absolute calibrations of most participants of the NOGIC'96 (14 out of 17) and SUSPEN intercomparisons (17 out of 19) to the same NSL, NIST *[Johnsen et al. 1997, SUSPEN 1998]*. The discrepancy between the scales of the participants of the first two North American intercomparisons was up to 10% in the first two campaigns based on calibrations performed indoors and outdoors *[Thompson et al. 1997, Early et al. 1998a]*. In the third American intercomparison, the scales of the participants agreed with the NIST scale within 5% in darkroom, but calibrations outdoors indicated discrepancies up to tens of per cent for some instruments *[Early et al. 1998b]*.

3.3 Development of the scale of UV irradiance maintained by STUK

The scale for the spectral UV irradiance in Finland was established by STUK in 1989 *[Publ. III]*. Table 1 illustrates the history of the UV irradiance standards between 1989 and 2002 and Fig. 3 depicts the differences between the scales based on these standards.

***Table 1**. Standard lamps at STUK in 1989 through 2002.*

Year	Lamp Type	Manufacturer /traceable to	Reference standard No.	Uncertainty [1] (*k*=2)	Working standard No.	Uncertainty (*k*=2)
1989	DXW, 200 W	GE/OL	M-623	1.66% @ 250 nm 1.05% @ 350 nm	M-677	20% @ 250 nm 5% @ 350 nm
1990			M-676			
1993	FEL, 1000 W	GE/OL	F319	1.63% @ 250 nm 1.12% @ 350 nm	F320	11.6% @ 250 nm 3.3% @ 350 nm
1994		GE/NIST	F329 [2]	1.82% @ 250 nm 1.09% @ 350 nm		4.1% @ 250 nm[4] 1.6% @ 350 nm[4]
1996		Osram/NIST	F434 [3]			
		GE/GO	BN-9101-165 [5]	12.3% @ 250 nm 4.8% @ 350 nm	BN-9101-164 BN-9101-166[2] BN-9101-174	
1998		Osram/NIST	F491	1.82% @ 250 nm 1.09% @ 350 nm		
1999		Osram/HUT	F434, F491	2.7% @ 291 nm[6] 1.4% @ 352 nm[6]		3.1% @ 291 nm 1.8% @ 352 nm
2002	DXW, 1000 W	GE/HUT	D15	2.3% @ 300 nm 1.6% @ 350 nm		

GE: General Electric, U.S.A.
GO: Gigahertz-Optik, Germany, accredited laboratory, traceability to PTB.
OL: Optronic Laboratories, Inc., U.S.A., traceability claimed to NIST.
[1] As specified in the certificate.
[2] Unstable lamp, replaced with new lamp by supplier.
[3] The main reference standard at STUK since 1996.
[4] *[Jokela et al. 2000]*
[5] Calibration of the lamp was erroneous by ca. 10% when first received and it was recalibrated by GO.
[6] *[Kübarsepp et al. 2000]*

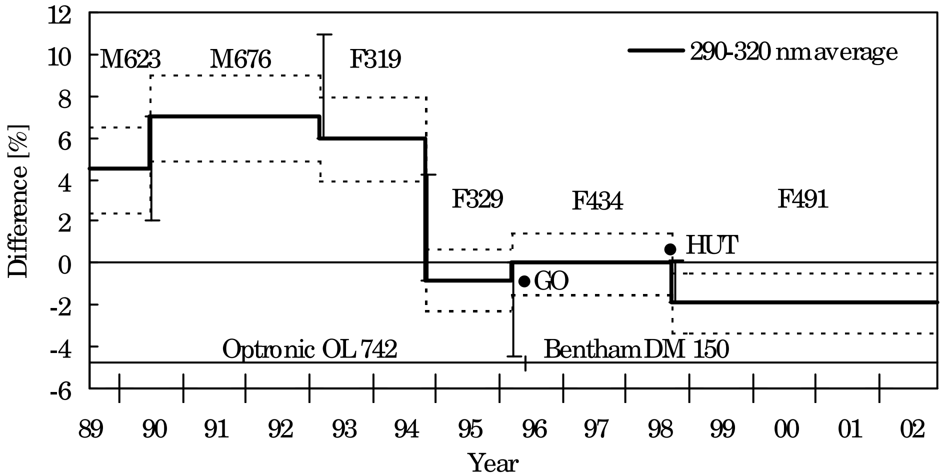

Figure 3. *Changes in the UV irradiance scale maintained by STUK. The baseline is defined by the main reference standard, the 1000-W FEL lamp F434 from NIST. The error bars give the uncertainty (k=2) of successive intercomparisons. Dashed lines give the uncertainties of the lamps as specified in the calibration certificates [Jokela et al. 2000].*

Calibrations were started using a single standard lamp purchased from Optronic Laboratories, Inc., U.S.A., reporting traceability to NIST but without any certified documentation for this. As long as the successive standard lamps were purchased from the same supplier, the scale remained the same within measurement uncertainties. The importance of the direct traceability to an NSL was underlined by the striking change of ca. 7% in the UV irradiance scale when the first lamp (F329) directly traceable to NIST was taken into use (Table 1, Fig. 3).

The output from the F329 lamp from NIST was not stable but instead showed time-to-time instabilities of the order of 5%. Moreover, a sudden change of 2% in irradiance occurred when the spectroradiometers were calibrated during the WMO/STUK intercomparison *[Publs. IV, V]*. In January 1996 the lamp was replaced by a new lamp (F434) from NIST. Before the F329 lamp had indicated any instability, the scale had been transferred to a stable working standard, F320 lamp, allowing comparison with the new F434 lamp used as main reference standard since 1996. The reliability of the STUK's present NIST-based scale is confirmed by the good agreement with the PTB-traceable scale disseminated by GO, the detector-based scale of HUT and the second reference standard (F491) from NIST *[Jokela et al. 2000, Kärhä et al. 2000]*. However, the fact that the calibration of a certified lamp (1000-W FEL, BN-9101-165, see Table 1) from an accredited calibration laboratory (GO) was erroneous by ca. 10% when first received at STUK[7], emphasizes the absolute necessity of having more than one certified secondary standard.

Analysis of the uncertainties of the standards presented in Table 1 shows some unexpected variations in the uncertainties of the reference standards as specified by the suppliers. First, the uncertainty of the 1000-W lamp F319 is higher at 350 nm than the uncertainty of the first two 200-W lamps. The reason is the change in the specification of the transfer uncertainty at OL. At 250 nm the transfer uncertainty had decreased by 0.1% and at 350 nm increased by 0.2%. The second apparent discrepancy occurs between the uncertainties of the last OL lamp, F319, and the first reference standard directly from NIST, F329. The uncertainty of the NIST lamp at 250 nm is unexpectedly higher than the uncertainty of the OL lamp. This is explained by the change in the method used for uncertainty assessment at NIST in 1992, when NIST adopted the *Guide to the Expression of Uncertainty*[8] *(GUM) [ISO 1995]* for expressing uncertainty in measurement. This led to expression of the uncertainties as combined uncertainties using coverage factor k=2 instead of k=3. Then, however, only the components due to random sources of error in the uncertainty were changed accordingly; the uncertainties due to systematic sources of error remained unchanged *[Walker et al.1987, NIST 1994].*

It is not clear how the uncertainty of the lamps supplied by OL has been generated from the uncertainty of their reference lamp and the calibration method applied. In the light of the 7% difference between the lamps from OL and NIST, it is evident that the traceability of the OL lamps did not fulfil the requirements for compatible solar UVR measurements.

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[7] Before the calibration for STUK, GO had been calibrating at a distance of 70 cm, whereas STUK specified 50 cm for the calibration distance. This led to circumstances where an error of ca. 10% was generated.

[8] Publication of GUM was the end point of a lengthy process initiated by the Comité International des Poids et Mesures (CIPM) in 1977. The task was to arrive at an internationally accepted procedure for expressing measurement uncertainty and for combining individual uncertainty components into a single total uncertainty. The problem was addressed by the Bureau International des Poids et Mesures (BIPM) together with the NSLs and various standardisation and metrology organisations. The end result, GUM, has been a crucial tool in reaching international consensus on expressing uncertainty in measurement. [ISO 1995] The European Accreditation (EA) has condensed the principles of GUM in the document EA-4/02 Expression of the Uncertainty of Measurement in Calibration [EA 1999].

Between 1989 through 2002, the overall number of reference standards at STUK increased from a single lamp from a non-accredited laboratory to three lamps calibrated by NSLs (NIST and HUT) and one lamp calibrated by a laboratory accredited by PTB. The number of working standards has increased from one lamp to altogether five lamps.

Table 1 demonstrates a significant improvement, from ca. 20% to 4.1% at 250 nm and from ca. 5% to 1.6% at 350 nm, in the uncertainty of the STUK working standards. This is partly due to the decrease in the uncertainty of the secondary standards, and partly due to the improved accuracy of spectroradiometric measurements after replacement of the OL 742 with the higher precision spectroradiometer Bentham DM 150 in 1996.

3.4 Solar UVR

Two main factors determine the solar UV irradiance reaching the ground: 1) the solar zenith angle θ_z, *i.e.* the angle between the local vertical direction and the direction of the centre of the solar disc and 2) the column of the total ozone. Besides these factors, clouds and aerosol content of the atmosphere have an effect on the relative spectral distribution. Of the extraterrestrial solar radiation, the UV-C (100-280 nm) radiation is completely blocked out by the atmosphere. Wavelengths longer than ca. 315 nm of UV-B (280-320 nm) as well as UV-A (320-400 nm) radiation penetrate the ozone layer without significant spectral attenuation, whereas the shorter wavelengths of UV-B are efficiently absorbed by the ozone layer (Fig. 4).

The solar UVR reaching the ground consists of the direct radiation from the Sun and the diffuse radiation scattered from the sky (Fig. 5). Because of Rayleigh scattering, the diffuse radiation component is particularly important at UV wavelengths. Even in clear sky conditions and at highest elevation angles, the diffuse component represents roughly 40% or more of the global UVR. Clouds and aerosols further increase the relative proportion of diffuse radiation. The real radiation field reaching a UV radiometer depends in a complex way on the various directions of incidence.

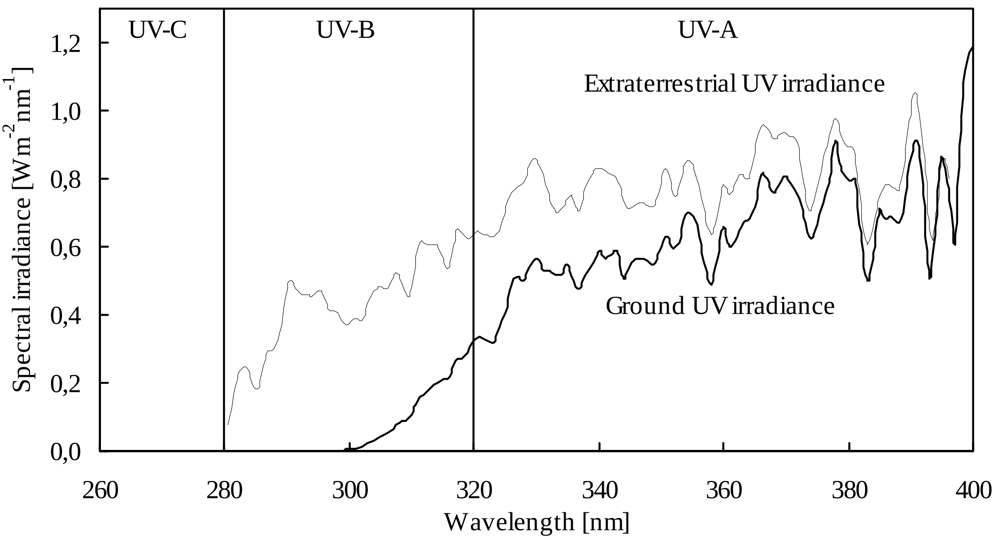


Figure 4. *Atmospheric transmission of the solar UVR.*

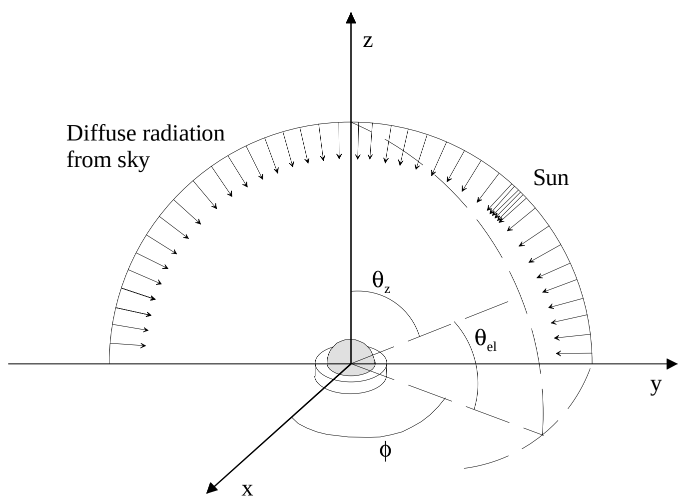


Figure 5. *Geometry of solar UVR measurements [Publ. I]*

3.4.1 Action spectra in the UV range

The sensitivity of organisms to UVR is strongly wavelength-dependent. The various effects of UVR as well as the responses to changes in atmospheric composition may be assessed if the wavelength-dependency of the biological effects, *i.e.* the biological action spectrum, $B(\lambda)$, is known. Different action spectra are obtained by determining the irradiance causing the specific response as a function of wavelength. The action spectra for DNA damage *[Setlow 1974]*, erythema (*i.e.* skin-reddening) *[McKinlay and Diffey 1987]* and skin cancer *[DeGruijl et al. 1994]* are shown in Fig. 6. Numerous other action spectra are presented in *[UNEP 1998]*. At present, the most widely used action spectrum in solar UVR measurements is the action spectrum of erythema, the wavelength dependency of the sensitivity of the human skin to develop a mild erythema when exposed to UVR, as proposed by McKinlay and Diffey *[1987]*. Recently, this action spectrum has been slightly modified by the CIE (Commission Internationale de l'Eclairage) for the wavelength range of 328 to 400 nm *[ISO 2000]*, but the difference is not significant. In this work both spectra are referred to as the CIE spectrum.

Table 2. *Relative erythemal sensitivity of human skin as defined by McKinlay and Diffey [1987] and by CIE [ISO 2000].*

Wavelength range [nm]	**Relative erythemal sensitivity**	
	McKinlay and Diffey 1987	***ISO 2000***
250 - 298	1.0	1.0
298 - 328	$10^{0.094(298-\lambda)}$	$10^{0.094(298-\lambda)}$
328 - 400	$10^{0.015(139-\lambda)}$	$10^{0.015(140-\lambda)}$

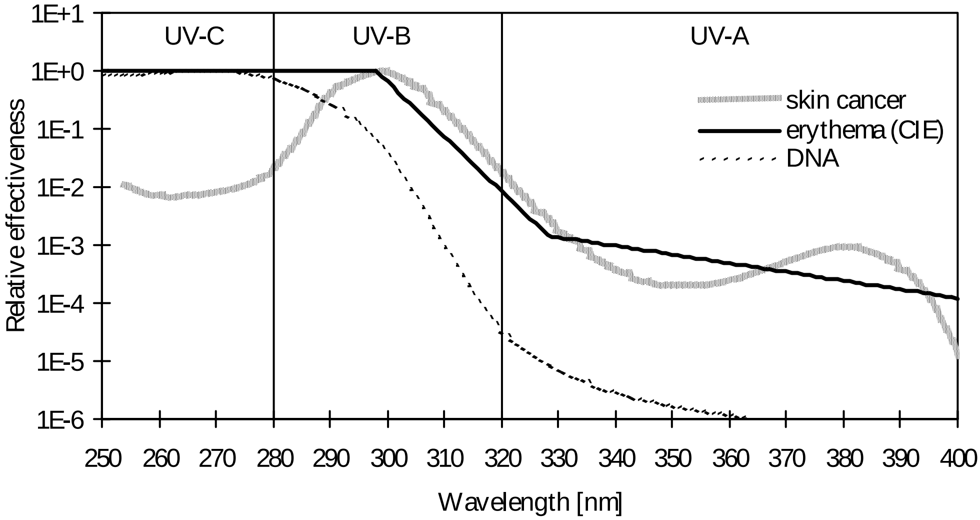


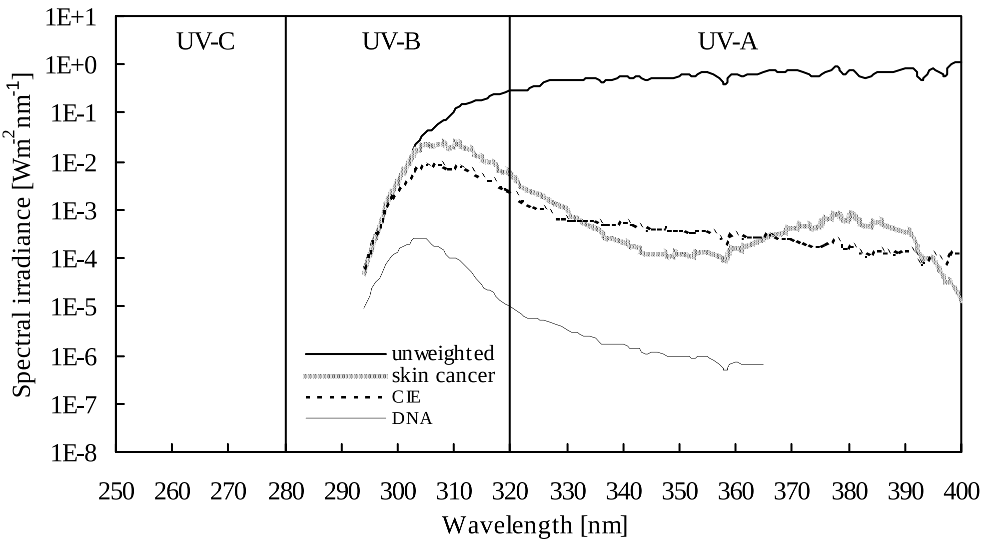
Figure 6. *UV action spectra for skin cancer [DeGruijl et al. 1994], erythema (CIE) [McKinlay and Diffey 1987] and DNA damage [Setlow 1974].*

3.4.2 Biologically effective UVR

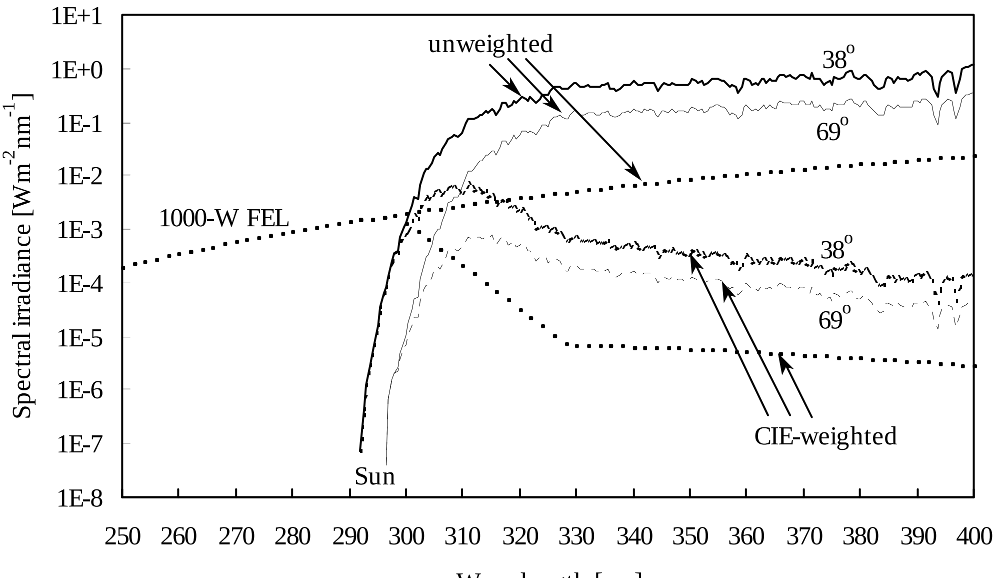
An estimate of the biological effect of the radiation is obtained by calculating the biologically effective irradiance (or dose rate), E_{eff}, *i.e.* the convolution integral of the biological action spectrum, $B(\lambda)$, and the measured spectral UV irradiance, $E(\lambda)$:

$$E_{\mathrm{eff}} = \int_{\lambda_1}^{\lambda_2} B(\lambda)E(\lambda)d\lambda \qquad (1)$$

The biologically effective solar radiation for the action spectra of skin cancer, erythema and DNA damage is shown in Fig. 7(a). The effect of solar zenith angle (θ_z) on the CIE-weighted solar irradiance is illustrated in Fig. 7(b). The unweighted solar spectrum in Fig. 7(a) and the spectra of a 1000-W FEL lamp commonly used in spectroradiometer calibrations in Fig. 7(b) are included for comparison. If only one type of measurement data is available, *e.g.* erythemally weighted measurement data, rough estimates for the other biological effects may be obtained by using theoretical correction factors *[Morys and Berger 1993, Jokela et al. 1993].*



(a)



(b)

Figure 7. *Solar irradiance weighted with skin cancer, CIE and DNA action spectra at solar zenith angle of 38° (a) and CIE-weighted solar spectra of zenith angles 38° and 69° (b). The unweighted solar spectrum (a) and the spectra of a 1000-W FEL lamp (at 50 cm distance) commonly used for spectroradiometer calibrations (b) have been included for comparison.*

As seen in Fig. 7(b), the erythemally weighted solar irradiance $B_\lambda E_\lambda$ (*i.e.* the CIE-weighted solar spectra) is at maximum at wavelengths around 308 to 310 nm. At shorter wavelengths the intensity of the terrestrial UVR is decreased due to strong attenuation by the ozone, while at longer wavelengths the sensitivity of the skin decreases.

The integration of equation (1) over the time from t_1 to t_2 gives the biologically effective dose (daily, yearly, etc.), H_{eff}, accumulated within the period $t_2 - t_1$:

$$H_{\mathrm{eff}} = \int_{t_1}^{t_2} E_{\mathrm{eff}}(t)dt = \int_{t_1}^{t_2}\int_{\lambda_1}^{\lambda_2} B(\lambda)E(\lambda,t)d\lambda dt \qquad (2)$$

In solar measurements, the erythemally effective UV dose is commonly indicated in Minimum Erythemal Doses (MED). One MED is defined as the dose required to elicit a just perceptible erythema reaction on normal previously unexposed and relatively sensitive Caucasian skin *[ISO 2000]*. By definition, the value of MED depends on the skin type. Values varying from 150 to 2000 Jm^{-2} can be found in the literature *[Sayre et al. 1981, Parrish et al. 1982, Pathak and Fanselow 1983, McKinlay and Diffey 1987, ISO 2000]*, while the most commonly used values range from 200 to 300 Jm^{-2}. In view of the variability of the definitions of MED, Jokela et al. *[1993]* suggested a new measure, standard erythemal dose, SED, of 200 Jm^{-2} to be applied for solar UVR measurements. This value, adopted by STUK, is comparable with the MED of 210 Jm^{-2} specified for the Solar Light meters. In 1996, the use of SED as a standardised measure of erythemogenic UVR was proposed by CIE *[1996]*, and in 1999, the SED was defined in an ISO standard as an equivalent to a CIE-weighted radiant exposure of 100 Jm^{-2} *[ISO 2000]*.

3.5 Spectroradiometric solar UVR measurements

Besides the uncertainties of primary and secondary standards, the most significant factors determining the absolute accuracy of solar UVR measurements are (i) non-ideal characteristics of the instruments, (ii) variation of the source to be measured (Sun and sky) and (iii) difficult outdoor conditions. To achieve conditions of traceable solar UVR measurements, all the components of uncertainty due to calibration and instrumental deviations from the ideal have to be determined. In the case of systematic sources of error, corrections should be applied to the measurement data to compensate for the error. After all corrections have been made, the residual uncertainty component due to the incomplete knowledge of the required value of the correction is not anymore systematic but a random uncertainty *[ISO 1995]*.

The complexity of assessing the uncertainties in solar UVR measurements has been recognised by the WMO. A detailed method of estimating the uncertainty of solar UVR measurements is included in the *Guidelines for Site Quality Control of UV Monitoring* published recently by WMO *[Webb et al. 1998]*. The standard method is designed to ensure comparability between measurement sites. *Specific Uncertainty Estimate Forms* are provided for spectral and broadband measurements separately. However, the actual uncertainty of a single measurement at a given site may deviate from the standard estimate. Recently, a thorough study on the actual uncertainties of measurements with solar UV spectroradiometers was presented by Bernhard and Seckmeyer *[1999]*.

The uncertainty of spectroradiometric solar UVR measurements depends in the first place on the accuracy of the complete calibration system and the methods applied for the calibrations. The measurement uncertainty is significantly increased relative to the calibrations, *i.e.* measurements of a point source at normal incidence, when the spectroradiometer is transferred outdoors for solar UVR measurements *[Publ. III, Leszczynski et al. 1994b]*. The reason for this is that the input optics receives a steeply changing spectrum of direct radiation from the Sun at varying elevation angles as well as diffuse radiation from the whole sky.

3.5.1 Calibration of a solar UV spectoradiometer

Ideally, the calibration of a spectroradiometer is carried out in a temperature-stabilised dark room with use of high-accuracy calibration equipment consisting of at least a lamp, a current source, a measuring system for the lamp current and voltage monitoring, an alignment system and baffles for stray light elimination. For reliable calibrations the calibration reference should consist of a set of three lamps *[Webb et al. 1998, Publs. III, IV]*. It is strongly recommended that any solar UVR measuring laboratory should trace its calibration lamps to calibration laboratories having a high level of metrological expertise and well-documented QC practice.

Besides the uncertainty of the standard lamp, the overall uncertainty of the calibration is affected by the uncertainty of the alignment of the calibration system, by the uncertainties of the current source, shunt resistor and voltmeter, and by the interpolation of the standard lamp irradiance function. The most critical single parameter is the uncertainty of the lamp current. The relative change in the spectral irradiance of a halogen lamp is approximately 5·(600/λ) times the relative error in current setting: an error of 0.1% in the current setting causes an uncertainty of 1.0% in the spectral irradiance at 300 nm *[Kostkovski 1997, Bernhard and Seckmeyer 1999]*. This ratio has been well known for a long time, but its significance becomes of special importance in this context. If the uncertainty of the reference standard is taken as specified by the NSL (1.46%), an overall uncertainty of 2.2% *[ISO 1995]* for the calibration of a spectroradiometer at 300 nm may be achieved with careful calibration procedures [*Jokela et al. 2000]*. Pursuing another approach, Bernhard and Seckmeyer *[1999]* concluded that a reasonable estimate for the uncertainty of present reference standards would be 3.5% leading to an overall calibration uncertainty of 3.8%. This uncertainty evaluation also applies for the calibration of working standards.

In the ideal case, the calibration of a spectoradiometer should not change when it is moved outdoors for solar measurements. It has been demonstrated, however, that the responsivity of solar UV spectroradiometers may change significantly upon transfer of the instruments from darkroom to field measurements *[Thompson et al. 1997, Early et al. 1998a,b,c]*. The exact causes of these changes are not yet known. Mechanical stress during the transfer, environmental factors such as heat or humidity or electromagnetic interference may be relevant.

Various prototypes have been built and more efforts are underway to develop reliable portable field calibrators *[Wester et al. 1997, SUSPEN 1998, Early et al. 1998c, Kärhä et al. 2002]*. A reliable field calibrator would be of particular advantage for the operation of often very large instruments (*e.g.* Brewer spectroradiometers) not easily brought indoors for laboratory calibration. Detector-monitored field calibrators eliminate the uncertainties due to instabilities of the lamps. Moreover, the shortest possible traceability chain from an NSL to field measurements is achieved with a detector-monitored field calibrator *[Kärhä et al. 2002]*.

3.5.2 Measurements of spectral solar UV irradiance

The non-ideal radiometric characteristics of the common spectroradiometers do not necessarily manifest themselves when calibration is done with a point source at normal incidence. In solar UVR measurements, knowledge of characteristics such as angular responsivity, slit function, wavelength accuracy and possible stray light problems of the spectroradiometer is of crucial importance. This is because of the complex distribution of the radiation from the Sun and sky and the steep increase in the solar irradiance, as much as three orders of magnitude, from 290 to 310 nm.

The basic measurement equation for a spectroradiometric solar UVR measurement at wavelength λ_o is

$$S(x,y,\theta,\phi,\lambda_o) = \int_{\Delta\lambda}\int_{\phi}\int_{\theta} R_{\Phi}(x,y,\theta,\phi,\lambda,\lambda_o)\, L_{\lambda}(x,y,\theta,\phi,\lambda)\cos\theta\sin\theta\, d\theta\, d\phi\, d\lambda\ , \qquad (3)$$

where $S(x,y,\theta,\phi,\lambda_o)$ is the output signal of the spectroradiometer, R_{Φ} is the flux responsivity of the spectroradiometer at wavelength λ_o, L_{λ} is the radiance of the Sun and sky, θ and ϕ are the zenith and azimuth angles of the flux element at the point x,y of the receiving aperture and at wavelength λ, and $\Delta\lambda$ is the bandwidth of the spectroradiometer, i.e. the wavelength interval over which the responsivity is not zero, $R_{\Phi}(\lambda,\lambda_o) \neq 0$. The flux responsivity is commonly assumed to be independent of the position x,y on the input optics.

3.5.3 Requirements for reliable spectroradiometric solar UVR measurements

The accuracy required of solar UV spectoradiometers depends on the objective of the measurements. Solar UVR measurements are carried out to (i) establish a UV climatology by world-wide long-term monitoring, (ii) to detect trends, (iii) to yield data for radiative transfer models and satellite-derived terrestrial UV data and for (iv) public information (*e.g.* UV index). The highest accuracy is required for measurements intended to reveal trends and to yield data for radiative transfer models. UV climatology and the UV index can be based on somewhat less accurate measurements.

Specifications for solar UV spectroradiometers together with the guidelines for instrument characterisation have recently been published by WMO. In this publication, Seckmeyer et al. *[2001]* present (i) an overview of current instrumental characteristics, (ii) define two types of solar UV spectroradiometers (type S-1 instruments for establishing UV climatology and type S-2 instruments for detecting a change in spectral UV irradiance resulting from a 1% change in total ozone column) and (iii) compile guidelines for characterisation of UV spectroradiometers. Specifications for S-1 and S-2 instruments are summarised in Table 3.

Table 3. *Recommended specifications for type S-1 and S-2 instruments [Seckmeyer et al. 2001].*

Quantity	**Quality**		
	S-1	**S-2**	
Cosine error [%]	< ±10 < ±10	< ± 5 < ± 5	(a) for incidence angles < 60° (b) for integrated isotropic radiance
Minimum spectral range [nm]	290-325	290-400	
Bandwidth (FWHM) [nm]	< 1	< 1	
Wavelength precision [nm]	< ± 0.05	< ± 0.03	
Wavelength accuracy [nm]	< ± 0.1	< ± 0.05	
Slit function	< 10^{-3} -	< 10^{-3} < 10^{-5}	of maximum at 2.5 FWHM away from centre of maximum at 6.0 FWHM away from centre
Sampling wavelength interval	<FWHM	<0.5·FWHM	
Maximum irradiance [$W/m^{-2}nm^{-1}$]	> 1 > 2	> 2	at 325 nm at 400 nm (noon maximum) (if applicable)
Detection threshold [$W/m^{-2}nm^{-1}$]	< $5 \cdot 10^{-5}$	< 10^{-6}	(for SNR = 1 at 1 nm FWHM)
Stray light [$W/m^{-2}nm^{-1}$]	< $5 \cdot 10^{-4}$	< 10^{-6}	When instrument is exposed to the SUN at minimum solar zenith angle
Temperature stability [ºC]	-	Typically < ± 2	Monitored and sufficiently stable to maintain overall instrument stability
Scan time [min/spectrum]	< 10	< 10	
Overall calibration uncertainty [%]	< ± 10	< ± 5	Unless limited by detection threshold
Scan date and time			Recorded with each spectrum such that timing is known to within 10 s at each wavelength

3.5.4 Improvement of the uncertainty of the spectroradiometric solar UVR measurements at STUK

The solar UVR measurements at STUK were started with the OL 742 spectroradiometer in 1989, and in 1996 the Bentham DM 150 spectroradiometer was taken into use. The importance of thorough characterisation of the radiometers, with evaluation of the overall uncertainties, was recognised in the early stage of the solar UV radiometry. Indeed, STUK was one of the first solar UVR monitoring laboratories reporting comprehensive uncertainty budgets for its solar UVR measurements *[Publ. III, Leszczynski 1994, 1996].*

The most essential improvements in the measurements with the first spectroradiometer, OL 742, were the numerical corrections to eliminate errors due to (i) non-ideal cosine response, (ii) inaccuracy of the wavelength scale and (iii) temperature sensitivity *[Publ. III]*. STUK was one of the pioneers in applying the theoretical cosine correction *[Publ. II]*.

The second spectroradiometer, a temperature-stabilised instrument of a newer generation of solar UV spectroradiometers with significantly improved angular responsivity, has been thoroughly characterised. The methods for correction of the inaccuracy of the wavelength scale and residual cosine error have been further developed. The non-linearity of the wavelength scale has been determined by using Hg-and Cd-lamps and the Fraunhofer lines in solar spectra. The wavelength shifts of measured solar spectra are determined by a method suggested by Slaper et al. *[Slaper et al. 1995, personal communication from Lasse Ylianttila, STUK].*

The specifications of the OL 742 and Bentham DM 150 spectroradiometers are presented in Table 4 and the estimated uncertainties in Table 5.

Table 4. *Specifications of the OL 742 and Bentham DM 150 spectroradiometers of STUK [Publs. II, III, personal communication from Lasse Ylianttila, STUK].*

Quantity	**Quality**		
	OL 742	**DM 150**	**Comment**
Cosine error [%]	< 12	< 2.5%	for incidence angles < 60°
	10	< 2	for integrated isotropic radiance
Spectral range [nm]	250-400		
Bandwidth) [nm]	1.7	0.6	FWHM
Wavelength precision [nm]	0.1	0.02	
Wavelength accuracy [nm]	0.15	0.04	OL 742: mercury lines DM 150: mercury lines and solar spectrum
Slit function	$2 \cdot 10^{-3}$	$2 \cdot 10^{-4}$ $2 \cdot 10^{-6}$	of maximum at 2.5 FWHM away from centre of maximum at 6.0 FWHM away from centre
Sampling interval [nm]	1	0.5	
Maximum irradiance [$W/m^{-2}nm^{-1}$]	10	100	at 400 nm (noon maximum) (1% filter used)
Detection threshold [$W/m^{-2}nm^{-1}$]	10^{-5}	$5 \cdot 10^{-7}$	for SNR = 1 at 1 nm FWHM
Stray light [$W/m^{-2}nm^{-1}$]	$< 10^{-5}$	$< 10^{-7}$	when instrument is exposed to the SUN at minimum solar zenith angle
Instrument temperature	1)	2)	1) monitored and corrected. 2) stabilised, stability < 1 ºC
Scan time [min]	6	4-12	per spectrum
Calibration uncertainty [%]	3.6	2.3	k=2
Scan date and time	Manual < 10 s	1 s	recorded with each spectrum such that timing is known to within 10 s at each wavelength

From a comparison of the specifications of the OL 742 and DM 150 (Table 4) with the requirements listed in Table 3, it can be concluded that the OL 742 does not meet the specifications for either S-1 or S-2 instruments. The DM 150 spectroradiometer meets the specifications for S-1 instruments when normal measuring routines are followed. It could, however, be classified as an S-2 instrument if a shorter sampling interval than 0.3 nm were used. The requirement for short sampling interval is important, among other things, for deriving trace gas concentrations. At STUK, however, the main purpose is the calibration of EW radiometers, for which the present sampling interval is considered to be adequate. A shorter sampling interval would increase the measurement time significantly, hence also the uncertainty of the EW meter calibration, and so nullify the improved accuracy of the wavelength scale *[personal communication from Lasse Ylianttila, STUK]*.

Table 5*. The uncertainty budget of erythemally weighted spectroradiometric solar UVR measurements* with *the OL 742 and Bentham DM 150 spectroradiometers of STUK [Publs. II, III, personal communication from Lasse Ylianttila, STUK].*

Source of uncertainty	**Uncertainty [%]**		**Note.**
	OL 742	**DM 150**	
Calibration	1.8	1.16	
Wavelength accuracy	1.5	1.0	± 0.15 nm
Temperature	1.5	0.5	OL 742: *T* correction DM 150: *T* stabilisation
Non-ideal cosine response	2.5	1.5	cosine correction
Azimuthal response	0.5	0.25	
Slit function	1.0	1.0	
Non-linearity	0.3	0.1	photomultiplier tube
Stray light	0.3	0.01	double grating
Instrument stability	0.5	1.0	
Random	1.5	1.0	
Combined standard uncertainty	**4.2**	**2.8**	
Expanded uncertainty (*k*=2)	**8.5**	**5.6**	

It should be noted that Tables 4 and 5 do not indicate the starting point for the characteristics of the OL 742 spectroradiometer nor the uncertainties of the OL 742 measurements as they were before the development of the crucial QC methods for solar UVR measurements. Without cosine correction, the solar irradiance would have been more than 10% underestimated, and without measurement of the Hg line at the beginning of each solar spectrum the wavelength shift would have been about 0.5 nm, yielding about 10% error in the CIE-weighted UV-irradiance. Without temperature correction, a difference of ± 5 ºC in the temperature of the optics head at calibration and measurement causes an error of ± 5% in the CIE-weighted solar UVR measurement. It can be concluded that the overall uncertainty of spectroradiometric solar UVR measurements has been decreased from a level of approximately ± 20% with the non-characterised OL 742 without any corrections down to ± 5.6% with the well-characterised DM 150 spectroradiometer after data correction and application of stringent QC methods.

3.6 Broadband solar UVR measurements

3.6.1 Types of EW radiometers

The most widely deployed solar UV monitoring radiometers, the broadband EW meters, are designed to yield erythemally weighted UV irradiance. The spectral responsivity was developed so as to be similar to the response of human skin to UVR, and the angular response was developed to follow the cosine function. The basic design has not changed significantly since the introduction of the first EW meter, the Robertson-Berger (R-B) meter, in the seventies *[Robertson 1972, Berger 1976]*. The most essential improvements in EW meters have been the temperature stabilisation of the critical components and the built-in levelling spirit for horizontal alignment of the detector head. The makes of the most common EW radiometers and the numbers of each are presented in Table 6.

Table 6. *The most common EW radiometers deployed for solar UV monitoring and the numbers of each as of October 2002.*

Meter / manufacturer	Number
Scintec UV-S-290-T / Kipp & Zonen	160[1)]
SL 501/ Solar Light, Inc.	701[2)]
YES UVB-1 / Yankee Environmental Systems, Inc.	269[3)]
Total	**1130**

[1)] *Personal communication from B. Schrauf, Scintec AG*
[2)] *Personal communication from W. Eckman, Solar Light, Inc.*
[3)] *Personal communication from D. Sautter, Yankee Environmental Systems, Inc.*

Though details of the components and structures differ, the principle of operation of the meters is basically the same. First, the solar radiation incident on the weatherproof dome of the detector is filtered by a black prefilter that blocks the visible and infrared radiation. Then, the remaining UVR is converted to visible radiation by a fluorescing phosphor layer deposited on a green post filter. The fluorescence radiation through the green filter, which absorbs the residual

UVR, is detected by a photodiode. Differently from the other meters, the Scintec UV-S-290-T uses a Teflon diffuser under the quartz dome in front of the filters. STUK has tested altogether 41 EW meters, but apart from the 37 SL meters, all others were the single units of different type included in the WMO/STUK '95 intercomparison.

3.6.2 Measurement equation

Broadband measurements can be characterised with basically the same equation as the spectroradiometric measurements,

$$S(\theta,\phi) = \int_{\Delta\lambda}\int_{\phi}\int_{\theta} R_{\Phi}(\theta,\phi,\lambda)\, L_{\lambda}(\theta,\phi,\lambda) \cos\theta \sin\theta \, d\theta \, d\phi \, d\lambda \, , \tag{4}$$

where $\Delta\lambda$ denotes the wavelength range where the flux responsivity, R_{Φ}, of the radiometer is significantly non-zero. The flux responsivity has been assumed to be independent of the position x,y on the input optics. The radiance L_{λ} is assumed not to vary significantly within the area of the receiving aperture. Normally the meter is directed towards zenith and the integration is extended over the full hemisphere $\omega = 2\pi$.

The definition of the radiance is

$$L_{\lambda} = \frac{d^3\Phi}{dA \cos\theta \, d\omega \, d\lambda} = \frac{dE_{\lambda}}{\cos\theta \, d\,\omega} \, , \tag{5}$$

where

$$E_{\lambda} = \frac{d^2\Phi}{d\lambda \, dA} = \int_{\omega} L_{\lambda} \cos\theta \, d\omega = \int_{\phi}\int_{\theta} L_{\lambda} \cos\theta \sin\theta \, d\theta \, d\phi \, , \tag{6}$$

is the spectral irradiance at the surface element dA of the receiving aperture within the solid angle $d\omega = \sin\theta d\theta d\phi$. When all rays from the full hemisphere of an iso-radiance source are included, the integration of equation (6) gives

$$E_\lambda = L_\lambda \int_0^{2\pi}\int_0^{\pi/2} \cos\theta \sin\theta \, d\theta \, d\phi = L_\lambda \, \pi \int_0^{\pi/2} 2\cos\theta \sin\theta \, d\theta = L_\lambda \, \pi \, (\sin^2 \frac{\pi}{2} - \sin^2 0) = L_\lambda \, \pi \, . \qquad (7)$$

Assuming that there is no azimuth dependence and that the angular and spectral responsivities are separable, the flux responsivity becomes

$$R_\Phi = K \, r(\lambda) C(\theta) \, , \qquad (8)$$

where K is the calibration factor, $r(\lambda)$ is the spectral responsivity of the radiometer and $C(\theta)$ is the relative cosine responsivity indicating the deviation of the relative angular responsivity $A(\theta)$ from the ideal cosine function, *i.e.* the relative angular responsivity can be expressed as $A(\theta) = C(\theta) \cos(\theta)$.

Under clear skies the sun is approximated with a point source, and the diffuse radiation is assumed to be distributed isotropically over the whole sky. The total radiance is obtained as a sum of the direct radiance and the isotropic radiance: $L = L_{\text{dir}} + L_{\text{dif}}$. Equation (4) becomes

$$S(\theta, \phi) = K \int_{\Delta\lambda}\int_{\phi}\int_{\theta} C(\theta) r(\lambda) \left[L_{\lambda,\text{dir}}(\theta, \phi, \lambda) + L_{\lambda,\text{dif}}(\lambda) \right] \cos\theta \sin\theta \, d\theta \, d\phi \, d\lambda \, , \qquad (9)$$

where the direct radiation component from direction (θ_o, ϕ_o) is

$$L_{\lambda,\text{dir}}(\theta, \phi, \lambda) = \pi \, L_{\lambda,\text{dir}}(\theta, \phi, \lambda) \delta(\theta - \theta_o) \delta(\phi - \phi_o) \, , \qquad (10)$$

where δ is the Dirac delta function. The Dirac delta function, in general form $\delta(x-y)$, vanishes when $x \neq y$ and tends to infinity at $x = y$ so that $f(x) = \int f(y) \delta(x-y) dy$. This also implies that $\int_{-\infty}^{\infty} \delta(x) \, dx = 1$.

The assumption of approximately isotropic sky radiance under clear skies has been validated for UV-B radiation by measurements of spatial variations of the sky radiance *[Blumthaler et al. 1996]*, but the assumption is no longer valid in UV-A. At longer wavelengths this assumption underestimates the true diffuse cosine error by as much as 10% at 500 nm *[Groebner et al. 1996]*. Landelius and Josefsson *[2000]* showed that, in model calculations, at solar elevations higher than 40°, the R-B-weighted clear sky radiance is relatively isotropic, whereas at low solar elevations the maximum diffuse radiance is positioned in the solar azimuth direction but slightly shifted to the zenith. They found that the difference between the cosine correction factors based on isotropic and anisotropic sky radiance was ca. 3%, while the correction factors based on the assumption of isotropic sky irradiance varied from approximately 1.30 at solar elevation of 25° to 1.13 at elevation of 60°.

With the assumptions made above, equation (9) becomes

$$S(\theta_o) = K\left[C(\theta_o) \int_{\Delta\lambda} r(\lambda) E_{\mathrm{dir}}(\lambda,\theta_o) d\lambda + 2\int_0^{\pi/2} C(\theta)\cos\theta\sin\theta d\theta \int_{\Delta\lambda} r(\lambda) E_{\mathrm{dif}}(\lambda,\theta_o) d\lambda \right], \qquad (11)$$

where θ_o is the solar elevation angle, $E_{dir}(\lambda)$ is the direct spectral irradiance on a horizontal plane and $E_{\mathrm{dif}}(\lambda)$ is the diffuse spectral irradiance from the sky.

The relative cosine response, $C(\theta)$, can be determined from the cosine response measurements and $r(\lambda)$ from the spectral responsivity measurements. The direct and diffuse components of solar UV irradiance, $E_{\mathrm{dir}}(\lambda)$ and $E_{\mathrm{dif}}(\lambda)$, are based on measurements or model calculations. At STUK, Green's UV model for clear skies *[Green et al. 1980]* has been found to be in good agreement with measurements in Helsinki *[Jokela et al. 1993, 1995]*. In general, the spectral irradiance varies as a function of solar elevation angle, albedo, total ozone and aerosol contents, and cloudiness. It is not easy to take the last two variables into account in UV models and we therefore make the assumptions of a clear sky and low aerosol content.

The Green-model-based cosine correction has also been compared with the more rigorous correction based on the UV model of Stamnes et al. *[1988]* for radiation transfer. The Stamnes-model-based correction (for the CIE-weighted spectrum) utilises the measured ratio direct/diffuse and takes into account non-isotropic distribution of the sky radiance. Within the range of solar elevations 10 to 53°, the correction agreed within ca. 2% with the corrections based on Green's model. Furthermore, a calculation of the cosine correction based on the measured distribution of the ratio direct/diffuse with the DM 150 and on the assumption of an isotropic distribution of the diffuse radiation (without using any model) agreed within 1% with the calculations made with Green's model *[Publ. V]*.

3.6.3 Spectral and angular responsivities

Biological response of human skin to UVR varies with the individual, but for the global evaluation of UV-related health effects to succeed, broadband measurements have to be standardised, which means that the radiometric characteristics of all meters should be identical. The spectral responsivity, $r(\lambda)$, of every meter should follow exactly the same reference action spectrum and angular response should not deviate from the cosine response. The most commonly used reference spectrum today, and a suitable model for the ideal spectral responsivity, is the CIE action spectrum of erythema *[McKinlay and Diffey 1987]*. Hence, the spectral responsivity of an ideal EW radiometer should follow the CIE curve, *i.e.* $r(\lambda) = B_{\text{CIE}}(\lambda)$, and the angular responsivity should follow the $\cos\theta$ function.

Unfortunately, the angular and spectral responsivities of EW meters are far from ideal; moreover, the characteristics vary from one meter unit to another, even within the same meter type *[Publs. III-V]*. Figure 8 illustrates the spread of the measured spectral responsivities and Fig. 9 presents the deviations of the measured angular responses from the ideal cosine response *[Publ. V]*.

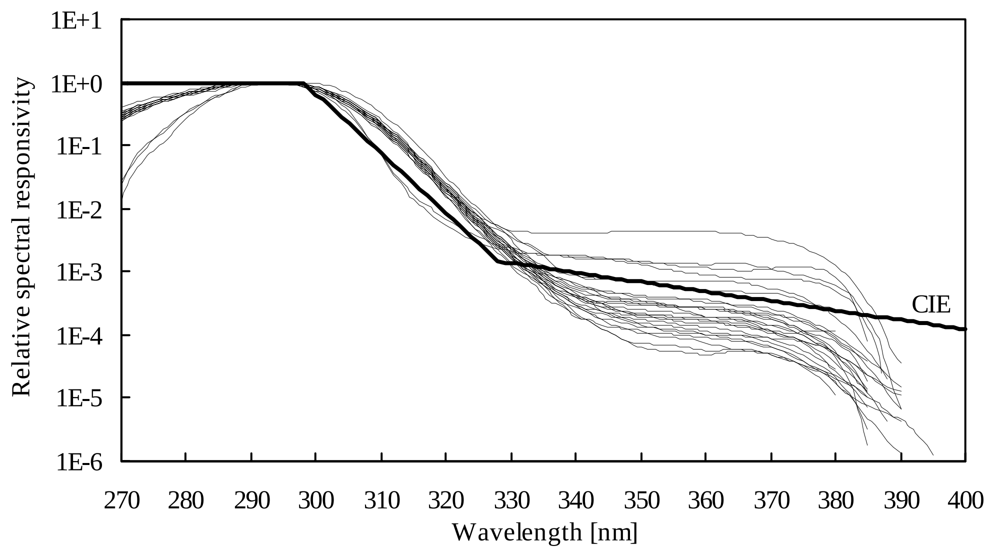


Figure 8. *Spectral responsivities of 20 EW meters measured at STUK [Publ. V]. The CIE action spectrum has been included for comparison [McKinlay and Diffey 1987].*

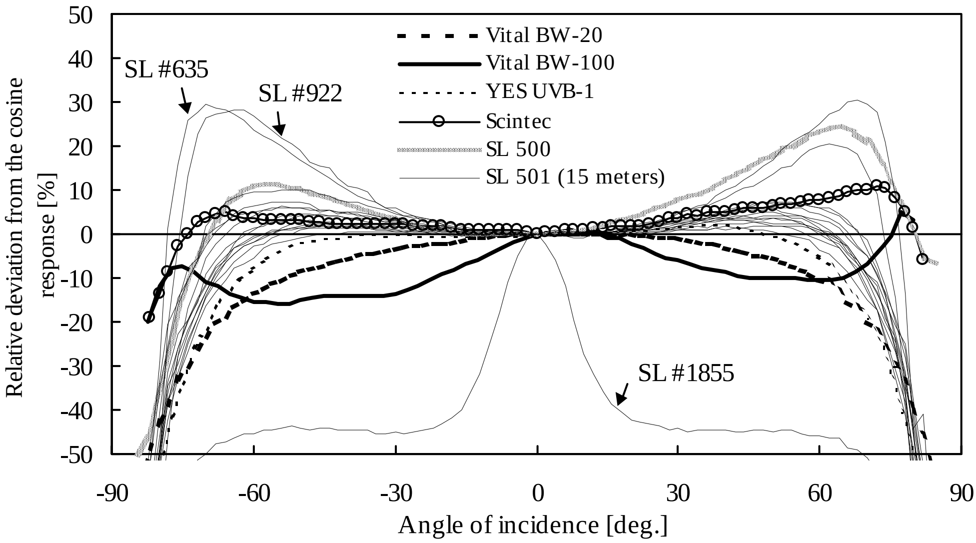


Figure 9. *Deviations of the angular responses of 20 EW meters measured at STUK from the ideal cosine response [Publ. V].*

As shown in Fig. 8, the spectral responsivities significantly overestimate the erythemal sensitivity in the UV-B range, whereas underestimation of the erythemal sensitivity is evident in the UV-A range. The angular response of the EW meters illustrated in Fig. 9 deviates within + 30/-20% from the ideal cosine response when the angle of incidence is within ± 70°. At 80°, the cosine response is typically underestimated by 50%, except for the Scintec and Vital BW-100 radiometers, which did not show more than ca. 20% underestimation at any angle of incidence. At high angles of incidence, the deviations become so high that it is necessary to measure the angular and spectral responsivities to find out the actual similarities, or rather dissimilarities, between meter units. The meter responsivities are also needed for determining correction factors to convert the measurement data to cosine-corrected CIE-weighted irradiance. Repeating the measurements of the angular and spectral responsivities at regular intervals provides crucial information on the stability of the meters.

The effect of deviation of the angular responsivity from the cosine function can be defined by computing the cosine correction factor as a ratio S_{CIE}/S, where S_{CIE} is the output given by an ideal CIE meter, free from any cosine error [$C(\theta) = 1$ and $r(\lambda) = B_{CIE}(\lambda)$], and S is the simulated output of the actual meter when the measured cosine response is used in conjunction with the CIE weighting function. Similarly, the spectral responsivity correction factors can be computed by using the ideal cosine function and measured spectral responsivity for *S [Publs. II-V]*. The correction factors corresponding to the spectral and cosine response data in Figs. 8 and 9 are presented in Figs. 10 and 11 *[Publ. V]*. The correction factors have been computed by using measured spectral irradiance, where the ratio of the direct and diffuse irradiance components is based on Green's model *[Green et al. 1980]*. The overall correction is a product of these two ratios.

As displayed in Fig. 10, the average values for the cosine correction factors for the EW meters vary from 0.9 to 1.1. The cosine correction factors of EW meters are seen to vary slightly less as a function of solar elevation angle than the correction factors for the spectroradiometers at the time of the WMO/STUK '95 intercomparison. However, the deployment of the new generation diffuser (J1002) for the DM 150 of STUK improved the cosine response of the spectroradiometer dramatically. The cosine correction factor for DM 150 is within 1.5% of unity and the variation as a function of solar elevation angle is less than 2%.

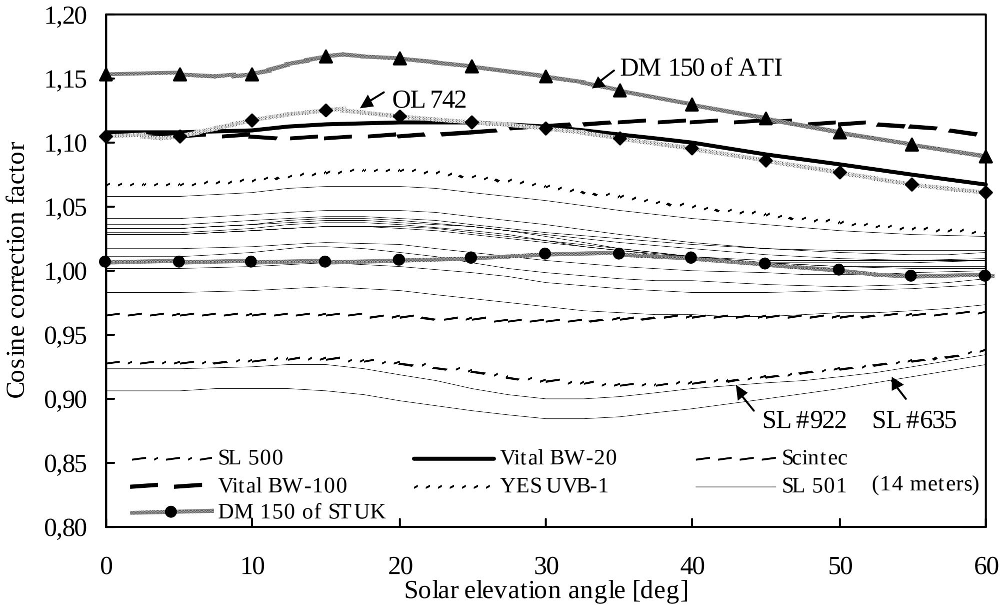


Figure 10. *Computed cosine correction factors as a function of solar elevation angle for the EW radiometers tested in the WMO/STUK intercomparison, based on measured spectral irradiance and Green's model. The data for the OL 742 and Bentham DM 150 spectroradiometers of STUK and ATI are included for comparison [Publ. V, personal communication from Lasse Ylianttila, STUK).*

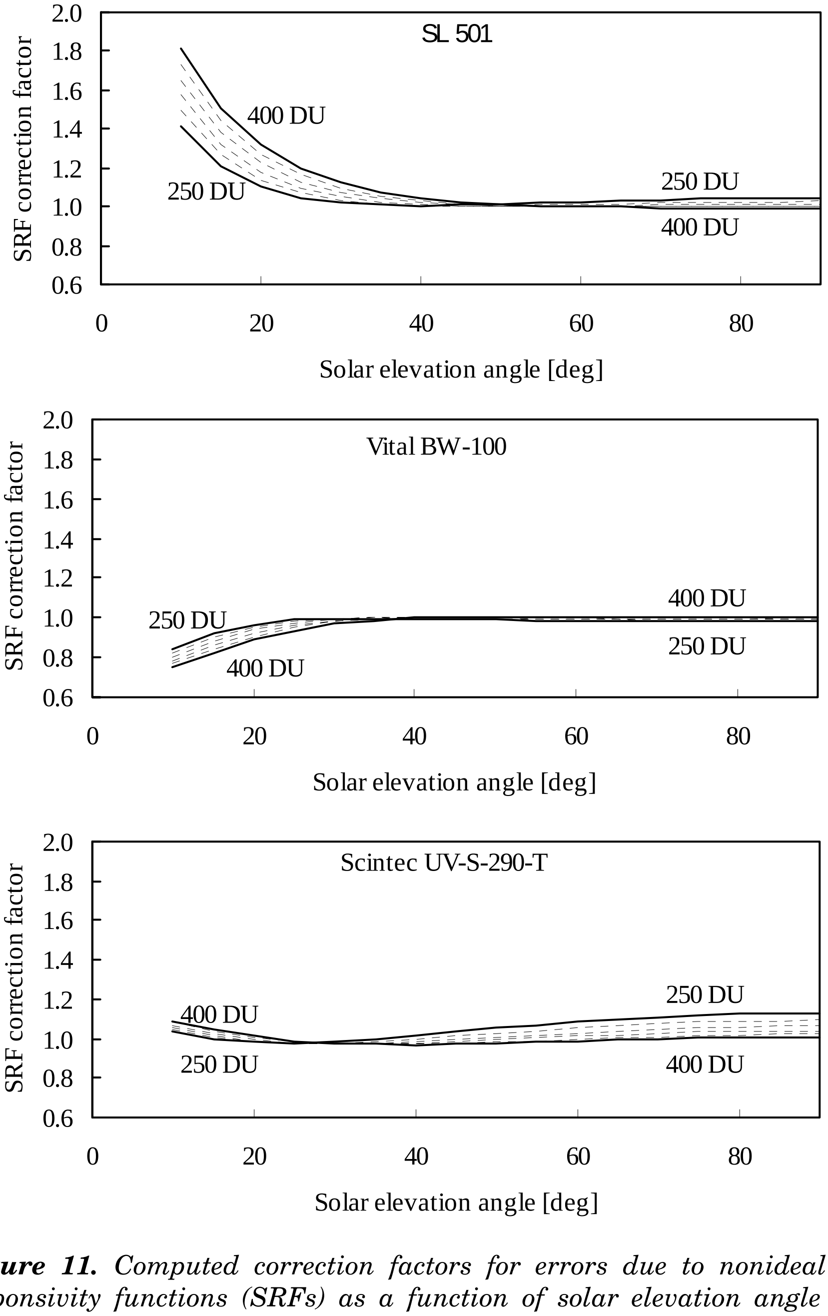


Figure 11. *Computed correction factors for errors due to nonideal spectral responsivity functions (SRFs) as a function of solar elevation angle for total ozone contents 250-400 DU for SL 501, Vital BW-100 and Scintec UV-S-290-T EW meters. The correction factors have been normalised to unity at ozone content of 325 DU and solar elevation of 50° [Publ. V].*

As can be seen in Fig. 11, the correction factors for eliminating the spectral responsivity error of SL meters typically increase by 40 to 80% from solar elevation of 50° down to 10° for total ozone contents of 250 DU and 400 DU, respectively. At high solar elevations the elevation-angle-dependent variation of the correction factors is within 5%. Correction factors for the YES UVB-1 meter (one unit, data not shown) are similar to those for the SL meters, whereas those for the Scintec UV-S-290-T and Vital BW-100 (and also BW-20) meters indicate less than ca. 20% variation at any solar elevation [Publ. V].

3.6.4 Temperature sensitivity and humidity

Besides the non-ideal angular and spectral responsivities, the response of EW meters changes with certain environmental factors, *i.e.* K and $r(\lambda)$ may change, *e.g.* as a function of temperature and humidity. In fact, one of the most significant sources of uncertainty of EW measurements with the meters lacking temperature stabilisation has been the temperature sensitivity of ca. 0.7 – 1%/°C *[Publ. I, Blumthaler and Ambach 1986, Jokela et al. 1991, Johnsen and Moan 1991].* Johnsen and Moan *[1991]* have reported also shifting of the spectral responsivity curve towards longer wavelengths with increasing temperature. Indeed, one of the most essential improvements in the design of the EW meters introduced in the early 1990s was the temperature stabilisation of the detector head. A correction method for minimising the errors in the past data caused by the temperature sensitivity of the old generation R-B meters (SL 500 meters) has been presented by Koskela et al. *[1994].* Another source of uncertainty of some EW meter types is exposure to moisture. The moisture-related problems can be controlled by changing the dessicator plugs regularly, as recommended *[Publ. V].*

3.6.5 Calibration of solar EW radiometers

Basically two different approaches have been applied for the calibration of EW meters: calibrations in the laboratory against lamps *[Jokela et al. 1991, Morys and Berger 1993]* and calibrations outdoors in solar radiation *[Publs. I-VI, Mayer and Seckmeyer 1996, Bodhaine et al. 1998, Lantz et al. 1999].* In both methods, the EW meters are calibrated against a high-accuracy spectroradiometer. EW meters have been calibrated against CIE-weighted or meter-response-weighted spectroradiometric data that is either cosine-corrected or not. To achieve globally comparable solar UVR measurements, however, the only viable option is to calibrate the EW meters in solar radiation on the basis of cosine-corrected CIE-weighted spectroradiometric UV data *[Publs. IV, V, WMO 1998]*. According to the recent recommendations of WMO, the absolute calibration for an EW meter must be obtained against a well-characterised/calibrated spectral radiometer under stable ambient solar radiation. Further it is recommended that the spectral reference data are weighted with the CIE erythemal action spectrum *[WMO 1998, Webb et al. 1998]*. However, for measuring temporal variation of UV levels at a single site, the monitoring data should be based on meter-response-weighted irradiance, because the CIE correction increases the uncertainty *[Publ. V, WMO 1998, Webb et al. 1998]*. Indeed, long-term stability and precision of the radiometer are more important for UV trend detection than is absolute accuracy.

Figure 12 presents a typical calibration result when the EW meter is calibrated against CIE-weighted cosine-corrected spectroradiometric data in solar radiation *[Publ. V]*. The calibration factors (CFs) are obtained by comparing the dose rate readings in $MEDh^{-1}$ with the CIE-weighted UV irradiance derived from the simultaneous spectral measurement from 290 to 330 nm converted to dose rate (1 $MEDh^{-1}$ = 210 $Jm^{-2}h^{-1}$ = 0.0583 Wm^{-2} as defined by the manufacturer). The systematic increase in the CFs at elevation angles lower than ca. 35° is mainly caused by the deviation of the spectral responsivity of the EW meter from the CIE weighting function and to lesser extent by the deviation of the angular responsivity from the cosine function. This is demonstrated with the two other sets of CFs included in Fig. 12, where the data was first corrected for the non-ideal spectral responsivity and then also for the angular responsivity.

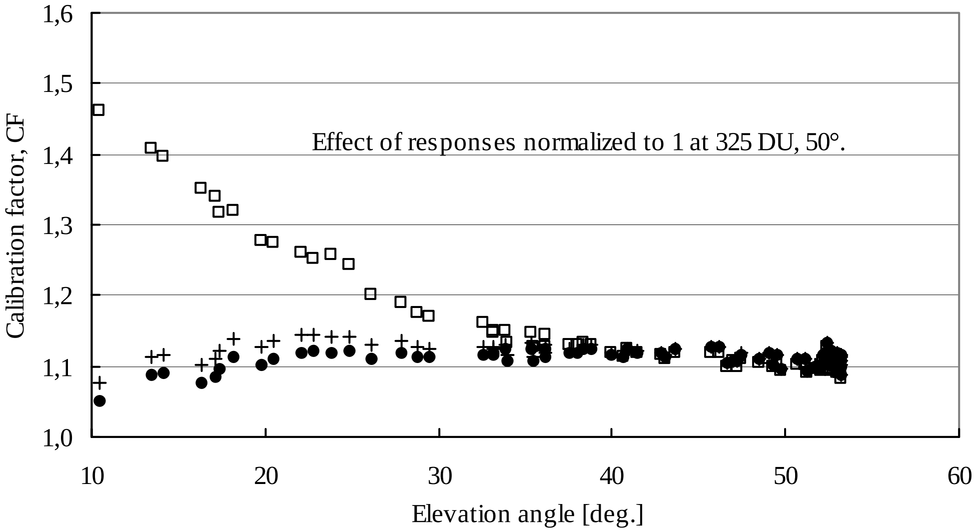


Figure 12. *The CFs of an EW radiometer type SL 501A V.3 (# 1466) based on spectroradiometric calibration in solar radiation on clear days during the WMO/STUK '95 intercomparison. The original CFs (□) were computed by using the cosine-corrected and CIE-weighted solar spectra measured with the DM 150 of ATI as a reference. In the second set of CFs (+), the effect due to non-ideal spectral responsivity was corrected by using the SRF correction factors presented in Fig. 11. In the third set of CFs (•) the effects due to both the non-ideal responsivities were corrected [Publ. V].*

The increase of the CFs towards the lower elevation angles is due to the typical decrease of the spectral responsivity of EW meters relative to the CIE-weighting function at longer wavelengths (Fig. 8), while the solar spectrum shifts towards shorter wavelengths at low solar elevations [Fig. 7(b)]. The random variation is caused mainly by the variations in atmospheric conditions, *i.e.* ozone content, cloudiness and aerosol content, but is also due to spectroradiometric uncertainty *[Publs. II, IV, V]*.

In view of the commonly appearing systematic increase of the CFs at solar elevations lower than ca. 35°, an approach to compare the calibrations of EW meters based on average values of CFs of elevation angles higher than 35° (denoted CF_{AVE}s) was adopted at STUK *[Publs. II-V]*. Table 7 presents the CF_{AVE}s of 20 EW meters obtained during the WMO/STUK intercomparison *[Publ. V]*.

Table 7. *CF_{AVE}s of the EW radiometers included in the WMO/STUK intercomparison based on cosine-corrected spectroradiometric measurements [Publ. V].*

No.	Radiometer manufacturer	Model	Serial number	CF_{AVE} [1)]
1.	Solar Light Co., Inc	500	421	0.87
2.		501 V.1	635	0.98
3.		501 V.3	910	1.26
4.		501A V.1	919	1.75 [2)]
5.		501 V.3	922	1.08
6.			1075	1.16
4			1081	1.26
8.		501A V.3	1087	1.11
9.		501 V.3	1120	1.20
10.			1450	1.16
11.			1466	1.11
12.			1468	1.24
13.		501A V.3	1492	1.15
14.		501 V.3	1855	1.15
15.			1861	1.16
16.		501A V.3	1896	1.08
17.	Yankee Environmental Systems, Inc.	YES UVB-1	920706	1.27
18.	Scintec Atmosphären Messtechnik GMBH	UV-S-290-T	010-A-00144	0.95
19.	Vital Technologies	Vital BW-20	9533	1.12
20.	Corporation	Vital BW-100	930100263	1.41

1) The CF_{AVE}:s were determined as an average of the results at solar elevations higher than 35° having as reference the CIE-weighted irradiance of 290 to 400 nm as measured with the Bentham DM 150 spectroradiometer of University of Innsbruck, 1 MED = 210 Jm^{-2}.

2) The owner of detector #919 had opened it to fix an operational fault.

A common feature of EW meters is the underestimation of the UV irradiance; half of the meters indicate irradiances that are 15-41% too low (Table 7). The CF_{AVE}s of the 13 SL model 501 V.3 meters were compatible with each other within 8%, while the deviation from the intercomparison calibration reference ranged from 8 to 26% *[Publ. V]*. The wide range of the average values of the CF_{AVE}s of all the meters, from 0.87 to 1.75, indicates that either the manufacturer calibration was no longer valid at the time of the intercomparison, or that the manufacturer calibration was not compatible with the calibration by STUK, for example due to the different method for calibration. Very few solar UV monitoring laboratories currently have facilities for testing and calibrating EW meters. One option to achieve better compatibility between UV data from independently operated EW radiometers would be to establish regional calibration centres *[Publs. IV, V]* where EW meters could be tested and calibrated.

WMO recommends calibration of EW meters against a spectroradiometer in solar radiation *[WMO 1998, Webb et al. 1998]*. However, it is not necessary to calibrate all the network EW radiometers spectroradiometrically *[Publ. IV]*. It is sufficient to calibrate one or preferably a few EW radiometers against the spectroradiometer and then circulate the calibrated reference EW radiometer through the monitoring sites. Indeed, this is the most feasible approach for calibrating the network EW radiometers.

Relative to the commonly used spectroradiometers, which are relatively complicated to operate, sensitive and clumsy, difficult to transport and expensive, requiring high investment and operation costs, there are obvious benefits to using EW meters as transfer instruments. Furthermore, the use of a reference EW meter of the same type as the network radiometers is preferable, because the ratio of two EW radiometers (Fig. 13) with similar radiometric characteristics is more constant in varying outdoor conditions than the ratio of a spectroradiometer and a broadband radiometer. This becomes clear in a comparison of Fig. 12 (original CFs) with Fig. 13: at best, the variation in the ratio of the two EW meters is within 1% at all solar elevations. The requirement for good weather conditions is not as limiting for broadband calibrations as for spectroradiometric calibrations of the network instruments. Also, the calibration can be based on much more extensive data when an EW radiometer rather than a spectroradiometer is used as a reference. Note, however, that in the use of an EW meter as transfer instrument, the radiometric characteristics of all network radiometers must be known.

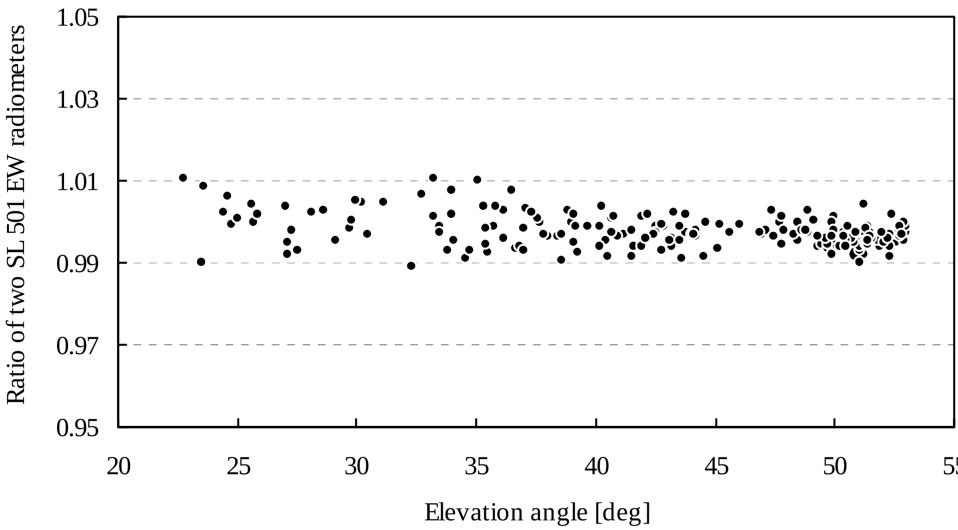


Figure 13. *Ratio of dose rates measured with two Solar Light Model 501 A EW radiometers having approximately angular and spectral responsivities [Publ. IV].*

3.6.6 Stability of EW meters

The longest records of UV data, for 1974-1985 from the first solar UV monitoring network of 14 R-B meters in the United States and analysed by Scotto et al. *[1988]*, were shown to be unreliable for long-term trend detection *[Frederick 1992, 1993, Kennedy and Sharp 1992, Weatherhead et al. 1997].* The definitive data required to assess long-term instrument performance often were not available, and it was concluded that the results of Scotto et al. probably were invalidated by drifts in calibration and instrument stability *[Kennedy and Sharp 1992, Weatherhead et al. 1997].* In particular, since the meters were not temperature-stabilised, the temperature sensitivity of the meters may have been a significant source of error *[Publ. I, Blumthaler and Ambach 1986, Johnsen and Moan 1991, Kennedy and Sharp 1992, Weatherhead et al. 1997].*

A decade has passed since temperature-stabilised EW meters were introduced, but long-term calibration and stability records are still sparse. STUK has collected annual calibration data for two reference EW radiometers since 1993. These two meters were also included in the WMO/STUK '95 intercomparison and in a follow-up study repeated four years later, in 1999, at STUK. In 1999, the same two meters were included in an intercomparison performed in Greece *[Bais et al. 2000]* to evaluate results obtained using different test methods and calibrations in different geographical locations. The results of the nine-year tests and calibrations at STUK and from the 1995 and 1999 intercomparisons are summarized below.

3.6.6.1 Long-term calibration data for two reference EW radiometers

Table 8 presents calibration records covering a period of nine years for the SL 501 model V.1 radiometer #635 employed at STUK and a period of eight years for the SL 501 model V.3 #1466 employed at FMI. Radiometer #635 is not operated during the winter, and meter #1466 is used only in calibrations and measurement campaigns. Hence, meter #1466, in particular, has not been exposed to prolonged environmental influence in real field use. The CF_{AVE}s of meter #1466 suggest good stability. The reason for the change of ca. 9% in the CF_{AVE} values when the reference spectroradiometer was changed from the OL 742 to the Bentham DM 150 is not known. The apparent changes in the calibration of the #635 are explained by the damage to the meter in a thunderstorm in 1993 and a leak in the case of the detector head, which damaged the detector, in 2000. The leak was observed one month after the calibration. In both cases, the meter was sent to the manufacturer for repair.

3.6.6.2 Intercomparison data for two reference EW meters

In 1999, STUK re-tested and re-calibrated the SL 501 meters #635 and #1466, which had been included in the WMO/STUK '95 intercomparison. The testing and calibration were done in the same location as in 1995 and using the same test methods as in 1995. In the same year (1999), the two meters were calibrated and tested in Greece by the University of Thessaloniki (UTH) in co-operation with the University of Innsbruck (ATI) *[Bais et al. 2001]*. The same DM 150 spectroradiometer of ATI that was used as a reference spectroradiometer at STUK in 1995 was used as reference spectroradiometer in Greece in 1999.

The average values of the CFs at solar elevations higher than 35° are presented in Table 9. The measurement data at STUK have been numerically corrected for the non-ideal cosine response of the reference spectroradiometer (DM 150 of ATI in 1995 and DM 150 of STUK in 1999).

***Table 8.** Calibration records of two SL 501 radiometers, model V.1 #635 of STUK and model V.3 #1466 of FMI. The CF_{AVE}s have been calculated as averages of CFs obtained at solar elevations higher than 35°. Here 1 MED = 200 Jm^{-2}.*

Year	Calibration factor, CF_{AVE} [1)		Reference spectroradiometer	Note
	SL V.1 #635	SL V.3 #1466		
1993	0.99	-	OL 742	#635 was sent to the manufacturer for repair
1994	1.07	1.24	OL 742	
1995	1.07	1.22	OL 742	OL 742 as a reference (not DM 150 of ATI)
1996	0.95	1.12	Bentham DM 150	OL 742 and DM 150 agreed within 2%
1997	0.91	1.12	Bentham DM 150	
1998	0.91	1.13	Bentham DM 150	
1999	0.93	1.16	Bentham DM 150	
2000	0.97	1.15	Bentham DM 150	#635 was exposed to humidity; dessicator plugs were changed
2001	0.89	1.14	Bentham DM 150	
2002	0.91	1.16	Bentham DM 150	

[1)] Owing to the different definition of MED (here 1 MED = 200 Jm^{-2}), the of CF_{AVE} values should be divided by 1.05 when comparison is made with the data in Tables 7 and 9, where 1 MED is defined as 210 Jm^{-2}.

***Table 9**. The average values of CFs of the SL 501 meters #635 and #1466 at solar elevations higher than 35°. Here 1 MED = 210 Jm^{-2}.*

Meter	Calibration factor, CF_{AVE}		
	1995 / STUK	1999 / STUK	1999 / Greece [1)]
# 635	0.98	0.89	0.882
# 1466	1.11	1.10	1.065

[1)] *Bais et al. [2001]*

The CF_{AVE}s obtained by STUK in 1995 and 1999 agree within calibration uncertainty, then estimated to be 10%. Also, the CF_{AVE}s obtained in Greece agree with the results obtained by STUK in 1999. However, the results for meter #635 meter suggest slightly increased sensitivity from 1995 to 1999, whereas the results for meter #1466 reflect the actual stability.

3.6.7 Improvement of the uncertainty of the EW measurements

The uncertainty of UV irradiance accumulates along the calibration chain from the primary standards through secondary standards to spectroradiometric measurements and further on to broadband measurements. Hence, all improvements in reference standards and spectroradiometric measurements lead to improved uncertainty of the EW measurements. Only the improvements in EW measurements are discussed below.

One approach to calculating the uncertainty of the CF_{AVE} of an EW meter is to add the standard deviation of the mean of the CFs at solar elevations higher than 35° to the uncertainty of the spectroradiometric measurement of CIE-weighted irradiance. The standard deviation of the mean of the CFs is typically 0.1-0.3%. This means that the expanded uncertainty (k=2) of the calibration of EW meters would be virtually the same as the uncertainty of spectroradiometric measurements (5.6%). Typically, calibrations are carried out on only a couple of days, however, perhaps once or twice a year. Hence, the CFs are exactly valid only (i) for the ozone contents, (ii) for the particular alignment of the instruments, (iii) for the particular error in timing of the simultaneous spectral and EW measurements and (iv) for the particular range of solar elevations prevailing during the calibrations. A second way to calculate the uncertainty is to use the knowledge of the radiometric characteristics of the meters and the range of the above-listed sources of error (i-iv) to obtain a generally valid estimate of uncertainty of CF_{AVE}s, not limited only to the actual calibration measurement. The uncertainty budget based on the latter approach is presented in Table 10.

The EW measurements at STUK began in 1991 with use of SL 500 meters that were not temperature-stabilised, and the first calibrations were performed in the laboratory against a solar simulator. A goal was set to reach uncertainty of less than 20% for CIE-weighted solar UVR measurements *[Jokela et al. 1991]*.

The first temperature-stabilised SL 501 meters were put into use in 1992. A new calibration method was developed: EW meters were calibrated in solar radiation against simultaneous CIE-weighted spectroradiometric measurements. Calibrations at solar elevations only higher than ca. 20° led to the assumption that the CFs would change linearly as a function of solar elevation angle. The uncertainty of temperature-stabilised EW measurements was estimated to be 11%. Also, the SL 500 meters without temperature stabilisation were modified by installing temperature sensors inside the detectors. The uncertainty of the SL

500 meters was estimated to be 19% without temperature correction and 14% with temperature monitoring and correction *[Publ. I]*.

Table 10. *The uncertainty budget of the spectroradiometric calibration of EW radiometers in solar radiation against CIE-weighted data.*

Source of uncertainty	**Uncertainty [%]**	**Note.**
Reference spectroradiometer	2.8	
Standard deviation of the mean of calibration data	0.3[1)]	$\sigma/\sqrt{n}$, where σ is the standard deviation of the CFs and n is the number of CFs
Spectral responsivity	2.5	
Cosine response	0.5	
Alignment	0.5	
Timing	0.5	
Random	0.5	
Combined standard uncertainty	**3.9**	
Expanded uncertainty (*k*=2)	**7.8**	

[1)] The value of standard deviation of the mean depends on the calibration data. For example the standard deviation of the mean was 0.2% for 1994 whole year, 0.1% for 2001 whole year, and 0.3% for a single day in 2001 *[personal communication from Lasse Ylianttila]*.

By 1994, data for nine temperature-stabilised EW meters had been analysed. Calibration and characterisation methods had further evolved. The variation of CFs of the EW meters as a function of the elevation angle was now shown to be non-linear, and the main reason for this variation, the deviation of the meter spectral responsivity from the CIE curve, was analysed *[Publ. II]*.

By 1995, methods for characterizing and calibrating EW meters were improved to the point where it was possible to organise the first intercomparison of 20 EW meters at STUK. In 1995 in the WMO/STUK intercomparison, and still in 1999, the uncertainty of the calibration of temperature-stabilised EW meters was estimated to be 10% *[Publs. III-VI]*. After adjustment of the method of uncertainty evaluation to follow more closely the ISO standard *[ISO 1995]*, the uncertainty of the calibrations of EW meters is estimated to be 7.8% (see Table 10).

4 Conclusions

It was realised in the early stage of the solar UVR measurements at STUK that the common standard of measurements was far from ideal, characteristics of instruments were non-ideal and, moreover, there were significant discrepancies in the UV scales disseminated by the NSLs.

During this study, a UV irradiance scale was established at STUK and the traceability of the NIST-based scale was confirmed by comparing it with the PTB-traceable scale and detector-based scale of HUT. STUK was one of the first solar UVR measuring laboratories to have reference standards from more than one NSL. This led to a significantly more reliable scale of UV irradiance, as HUT's detector-based scale allowed the shortest possible traceability chain to primary standards. Traceability to more than one NSL made it possible to reveal, and bring to common knowledge, that lamp standards even from NSLs may be erroneous by 5% to 9%. The combined uncertainty (k=2) of the UV working standard at STUK was improved from ca. 20% and 5% down to 4.1% and 1.6 % at wavelengths of 250 nm and 350 nm, respectively.

From the characterisations of the first few EW radiometers at the beginning of the 1990s, it was concluded that the radiometric characteristics of meters assumed to be identical were not in fact the same. Methods for instrument characterisation and calibration were accordingly developed. Thorough characterisation of radiometers and the development of methods for eliminating the systematic sources of error were the essential measures taken to improve the accuracy of solar UVR measurements at STUK. STUK was one of the first laboratories in the world to apply cosine correction to spectral data. It was also one of the first UVR-measuring laboratories to issue an uncertainty budget for solar UVR measurements. During this study, the uncertainty of spectroradiometric solar UVR measurements has decreased from ca. 20% down to 5.6% (k=2), and the uncertainty of the spectroradiometric calibration of the temperature-stabilised EW radiometers in solar radiation has decreased from ca. 11% to 7.8%.

In 1995, the WMO/STUK '95 intercomparison, the first international intercomparison of broadband EW radiometer and the most comprehensive exercise to date, was arranged at STUK with support from WMO and in cooperation with the University of Innsbruck. The methods for testing and calibrating EW radiometers developed at STUK were shown to be adequate.

Ten of the altogether 20 EW radiometers of six different types (make and model) indicated irradiances that were 15 to 41% too low. Even though 16 of the meters came from the same manufacturer, significant variations were found in both spectral and angular responsivities, clearly showing that radiometers assumed to be identical were not. 'Central' testing and recalibration of the meters significantly improved the accuracy and compatibility of the EW measurements. As a result, it was possible, for the first time, to trace calibrations of about 100 EW radiometers around the globe to the same origin.

The data collected in calibrations of EW radiometers at STUK over nearly 10 years indicate that the year-to-year changes of the calibration factors remain within estimated uncertainties. It is concluded that EW radiometers can yield reliable UV data with uncertainties comparable to those of spectroradiometric measurements, as long as stringent QC and QA methods are applied.

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Errata:

Publication I

Four sentences of the second paragraph on p. 170 should be corrected as follows.

The first sentence:
The doses should be in opposite order: 1.32 and 1.23 MED … 12.02 and 10.75 MED.

The third sentence:
The percentage 11% should be replaced by 12%.

The fourth sentence:
The percentages should be 15% (Feb.) and 4% (April).

The fifth sentence:
The number of the reference should be [12] instead of [10].

Publication III

The equation on p. 59 should be: $E_T = [1 + K_{\Delta T}(T - T_0)]E_0$.

In Fig. 4 on p. 59 and Table 1 on p. 60, the unit for the calibrated shunt resistor should be everywhere mΩ.

In paragraph 5.3.4 on p. 63, line 19 the units of dose rate given in parenthesis should be (1 MED/h = 200 J/m^2h = 0,0555 W/m^2).