Assessment and Comparison of Methods for Solar Ultraviolet Radiation Measurements

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ABSTRACT

The high precision measurements of solar ultraviolet (UV) radiation are needed for obtaining meaningful estimates of the terrestrial UV trends associated with the increasing levels of UV due to the depletion of the stratospheric ozone.

In this study, the different methods to measure the solar ultraviolet radiation are compared. The methods included are spectroradiometric, erythemally weighted broadband and multi-channel measurements. The comparison of the different methods is based on a literature review and assessments of optical characteristics of the spectroradiometer Optronic 742 of the Finnish Centre for Radiation and Nuclear Safety (STUK) and of the erythemally weighted Robertson-Berger type broadband radiometers Solar Light models 500 and 501 of the Finnish Meteorological Institute and STUK.

An introduction to the sources of error in solar UV measurements, to methods for radiometric characterization of UV radiometers together with methods for error reduction are presented. Reviews on experiences from world-wide UV monitoring efforts and instrumentation as well as on the results from international UV radiometer intercomparisons are presented.

Based on the studies carried out in STUK, the overall uncertainty of spectroradiometric measurements can be decreased from a level of approximately up to ±20 % down to ±8 % by thorough assessment of the radiometric characteristics like cosine response, slit function and temperature sensitivity together with stringent quality assurance and quality control procedures in calibration and actual measurements. The estimated uncertainty of the spectroradiometric calibration of the temperature stabilized erythemally weighted broadband meters in solar radiation is ±11 %. The ultimate limit for the lowest uncertainty possible to achieve in solar measurements is approximately from ±5 to 6 % is set by the absolute uncertainty of the primary standards.
The choice for the UV monitoring instrumentation depends on the quality of the problem to be addressed. To meet the needs to construct a global climatology and to evaluate the impact of UV radiation on human health and environment, numerous monitoring sites should be established. This necessitates the requirement to deploy easy to operate and low-cost instruments. Presently, the best choice for this purpose is the broadband erythemally weighted radiometers. On the other hand, to be able to provide reliable information for estimation of long-term trends in UV levels or for evaluation of radiative transfer models, a smaller number, but higher accuracy spectral instruments to be operated by trained personnel are needed.
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LIST OF SYMBOLS

\( \alpha \)  plane angle
\( \delta \)  Dirac delta function
\( \theta_z \)  solar zenith angle
\( \theta_{el} \)  solar elevation angle
\( \lambda \)  wavelength
\( \Delta \lambda \)  bandwidth
\( \mu \)  generalized cosine function
\( \phi \)  azimuthal angle
\( \Phi \)  radiant flux
\( \omega \)  solid angle
\( \Omega \)  projected solid angle
\( \eta_d \)  efficiency of diffuser
\( \eta_g \)  efficiency of grating
\( \tau_i \)  optical depth
\( A \)  area
\( A(\theta) \)  actual cosine response
\( B(\lambda) \)  biological action spectrum
\( C(\theta) \)  relative cosine response
\( D_\lambda \)  direct radiation component from the Sun (above atmosphere)
\( D_d \)  diameter of a diffuser
\( E \)  irradiance
\( E_{\text{eff}} \)  (biologically) effective irradiance
\( E_{\lambda}, E(\lambda) \)  spectral irradiance
\( E_0 \)  irradiance at reference temperature \( T_0 \)
\( E_T \)  irradiance at temperature \( T \)
\( f \)  focal length
\( G \)  geometrical extent
\( G_{\lambda} \)  global terrestrial radiation
\( h_s \)  slit height
\( H \)  radiant exposure
\( H_{\lambda}, H(\lambda) \)  spectral radiant exposure
\( H_{\text{eff}} \)  (biologically) effective exposure
\( K \)  cosine correction factor
\( K_\phi \)  calibration factor
\( K_1 \)  calibration factor
\( K_{\Delta T} \)  temperature coefficient
\( L \)  radiance
$L_\lambda$ spectral radiance
$L_D$ direct solar radiance component from the Sun
$L_S$ diffuse solar radiance component scattered from the sky
$N_j(y)$ distribution of the $j$:th atmospheric species as a function of height $y$
$P_{in}$ input power
$P_{out}$ output power
$R_\Phi$ instrument responsivity
$r_f$ responsivity factor
$r(\lambda)$ spectral responsivity
$s$ distance
$S$ output signal of an instrument
$S_\lambda$ diffuse radiation exposure component scattered from the sky
$t$ time
$T$ temperature
$T_0$ reference temperature
$U$ reading of a radiometer
$W_s$ slit width
$x$ coordinate
$y$ coordinate
$z(\lambda-\lambda_0)$ slit-scattering function
LIST OF ACRONYMS

ACGIH  American Conference of Governmental Industrial Hygienists
ARL    Australian Radiation Laboratory
BIPM   Bureau International des Poids et Mesures
CCPR   Comité Consultatif de Photometrie et Radiometrie of the Comité
        International des Poids et Mesures
CIE    Commission Internationale de l'Eclairage
FMI    Finnish Meteorological Institute
FWHM   Full Width at Half Maximum
IARC   International Agency for Research on Cancer
IFU    Fraunhofer Institute, Germany
MED    Minimum Erythemal Dose
NIST   National Institute of Standards and Technology, USA
NIWA   National Institute of Water and Atmospheric Research, New Zealand
NOGIC  Nordic Ozone Group InterComparison
NPL    National Physical Laboratory, U.K.
OL     Optronic Laboratories, Inc.
PTB    Physikalisch-Technische Bundesanstalt, Germany
QA     Quality Assurance
QC     Quality Control
RB     Robertson-Berger
SL     Solar Light Co.
SMHI   Swedish Meteorological and Hydrological Institute
STUK   Finnish Centre for Radiation and Nuclear Safety
UNEP   United Nations Environment Programme
UV     Ultraviolet
WMO    World Meteorological Organization
1 INTRODUCTION

High precision measurements of the solar ultraviolet (UV) radiation are necessary for the assessment of health and environmental effects associated with the depletion of the stratospheric ozone (UNEP 1991, WMO 1992, Young et al. 1993, Gibson 1991, Gibson 1992). The well-known detrimental effects caused by excessive UV exposures include erythema of the skin, kerato-conjunctivitis of the eyes, aging of the skin together with increase in cataracts, suppression of the immune system, activation of viruses and increasing incidence of carcinomas and melanomas. Ecological consequences of increasing UV levels may be widespread including damage to many terrestrial and marine organisms.

The decrease of the total ozone has been estimated to be approximately 5 to 8 % above the Northern Hemisphere (UNEP 1991, WMO 1992) but the results from the UV radiation measurements are contradictory (Scotto 1988, Bittar and McKenziel 1990, Blumthaler 1990, Correll et al. 1992, Kerr and McElroy 1993). The contradictory results may have been caused by the uncertainty associated with the measurement methods, variation in the cloudiness and the compensating effect of the air pollutants. So far, the increase in the UV radiation caused by the ozone depletion has been verified by the measurements only in Antarctica, where up to 70 % springtime ozone depletions have been reported (WMO 1992).

Decreased ozone values up to 40 % below the normal level were observed also in Finland during spring time in 1992 and 1993, and the measured maximal daily UV dose rates suggest an associated increase in UV (Jokela et al. 1993a, Jokela et al. 1993b). However, this increase was not statistically significant on most days due to the measurement uncertainty and lack of historical UV data. The significance of ozone depletion associated increase in UV exposure of the face and eyes has been shown to be considerably increased due to the reflection of UV radiation from the snow, especially in Northern Finland.

In Finland, solar ultraviolet irradiance has been measured since 1989 by the Finnish Meteorological Institute (FMI) at the Meteorological Observatory of Sodankylä (67.4°N, 26.6°E) and by the Finnish Centre for Radiation and Nuclear Safety (STUK) in Helsinki (60.2°N, 25.0°E). Three erythemally weighted broadband Solar Light Model 500 (denoted SL 500) radiometers have been continuously monitoring solar ultraviolet radiation since 1991 at the Meteorological Observatories of Sodankylä, Tikkakoski (62.4°N, 25.6°E) and Jokioinen (60.8°N, 23.5°E). In Sodankylä, solar UVB irradiance is measured with the Brewer MK II spectroradiometer. In 1994, FMI is going to replace the SL 500 radiometers with the newer model SL 501 A meters, and a Brewer MK IV
spectroradiometer will be deployed in Jokioinen. Besides the measuring sites listed above, FMI will install two more SL 501 A meters for continuous monitoring, one in Helsinki and another on the island of Utö (59.8°N, 21.4°E) off the southcoast of Finland. STUK has tested the SL 500 meters prior to their installations and all the new SL 501 A radiometers will be tested by STUK before they will be put into use, too.

The instrumentation of the STUK includes an Optronic 742 spectroradiometer together with the broadband SL 500 and SL 501 radiometers. The solar measurements by STUK are not carried out on regular basis, but rather for calibration and testing purposes and for collecting clear weather data for reference. STUK calibrates the SL radiometers of FMI annually at the observatories, and an intercomparison between the Brewer and Optronic 742 spectroradiometers is carried out on yearly basis, too. The calibrations and intercomparisons are carried out in solar radiation on clear weather during the period from May to September.

The assessment and comparison of the different methods for solar UV radiation measurements presented in this study is based on a literature review and the spectroradiometric measurements and broadband meter evaluations carried out in STUK within the period from summer 1989 to spring 1994.

This work can be divided in three parts: in chapters two to four, the theoretical considerations of UV measurements, the commonly used instrumentation and sources of error are introduced. The work done in STUK is introduced in chapters five and six, and in chapters seven and eight, the state-of-the-art of the world-wide UV networks, plans for the future and results from international intercomparisons are presented. The conclusions are given in chapter 9.
2 THEORETICAL CONSIDERATIONS

2.1 Solar UV radiation

The range of UV radiation (100...400 nm) is usually subdivided into UVA (320...400 nm), UVB (280...320 nm) and UVC (100...280 nm) regions based on physical properties and biological effects of each waveband. From extraterrestrial solar radiation the UVC radiation is completely blocked out by the atmosphere. The longest wavelengths of UVB as well as UVA radiation freely penetrate the ozone layer whereas the shorter wavelengths of UVB are efficiently absorbed by the ozone layer (Figure 1).

The two main factors determining the spectral distribution of the terrestrial solar UV radiation are 1) the zenith angle, $\theta_z$, the angle between the local vertical direction and the direction of the center of the solar disk, and 2) the column of the total ozone. Besides these factors, also clouds and aerosol content of the atmosphere have an effect on the relative spectral distribution.

![Figure 1. The atmospheric transmission of the solar UV radiation (Health Council of the Netherlands, 1994).](image)
The global terrestrial solar radiation, $G_\lambda$, consists of the direct radiation, $D_\lambda$, from the Sun (above the atmosphere) and the diffuse radiation, $S_\lambda$, scattered from the sky and is a function of the wavelength $\lambda$ and the solar zenith angle $\theta_z$:

$$G_\lambda(\lambda, \theta_z) = D_\lambda(\lambda, \theta_z) + S_\lambda(\lambda, \theta_z).$$  \hspace{1cm} (1)

The direct component $D_\lambda$ can be expressed (Green et al., 1980) as

$$D_\lambda(\lambda, \theta_z) = \cos \theta_z H_\lambda(\lambda) \exp[-\sum \tau_j N_j(y)/\mu_j],$$  \hspace{1cm} (2)

where $H_\lambda$ is the maximum irradiance falling on a surface directed towards the Sun, $\tau_j$ ($j = 1...4$) denotes the air, aerosol, water vapor and ozone optical depths, respectively, and $\mu_j$ ($j = 1...4$) are generalized cosine functions expressed as

$$\mu_j = \sqrt{\frac{\cos^2 \theta_z + t_j}{1 + t_j}}.$$  \hspace{1cm} (3)

In equation (3), the $t_j$:s are small characteristic numbers which depend on altitude distribution of the atmospheric component in question and $N_j(y)$ is the distribution of the $j$:th species as a function of height $y$. $N_j(y)$ is normalized to 1 at the ground level $y = 0$. The correction in the equation (3) accounts for the curvature of the earth. The mathematical model for the diffuse component and $N_j(y)$ distributions as well as the optical parameters can be found in Green et al. (Green et al. 1980). The components of the terrestrial ultraviolet radiation budget are illustrated in Figure 2.

Due to Rayleigh scattering, the diffuse radiation component is particularly important at UV wavelengths. Even at clear sky conditions and highest elevation angles the diffuse component represents roughly 40% or more of the global UV radiation. The relative proportion of diffuse radiation is further increased by clouds and aerosols. The real radiation field reaching a UV radiometer has a complex dependence on the various directions of incidence.
Figure 2. The budget of the terrestrial UV radiation.

2.2 Action spectra

The sensitivity of organisms to UV radiation is strongly wavelength dependent. The different effects of UV radiation as well as the responses caused by changes in atmospheric composition may be assessed, if the wavelength dependence of biological effects, i.e. the action spectrum, $B(\lambda)$, is known. The different action spectra are obtained by comparing the responses of exposed biological target to varying monochromatic wavelengths of radiation. The action spectra for the DNA damage (Setlow 1974), photokeratitis and erythema (ACGIH 1991), erythema (McKinlay and Diffey 1987), skin cancer (de Gruijl et al. 1993), phytoplankton photoinhibition (Mitchell 1990) and for higher plants (Caldwell 1986) are shown in Figure 3. Numerous other action spectra are found in UNEP 1991.

Presently, the most commonly used action spectrum in solar measurements is the action spectrum, $S_\lambda$, of erythema as proposed by the CIE (Commission Internationale de l'Eclairage) (McKinlay and Diffey 1987). For example, the spectral response of the Robertson-Berger type broadband radiometers used for monitoring the solar radiation is designed to follow the CIE action spectrum. The
Figure 3. Different UV action spectra.

CIE action spectrum follows roughly the sensitivity of the human skin to develop a mild erythema when exposed to the UV radiation.

2.2.1 Biologically effective radiation

The convolution integral of the biological action spectrum, $B(\lambda)$, and measured spectral UV irradiance, $E(\lambda)$, gives the biologically effective irradiance, $E_{\text{eff}}$, (or dose rate), an estimate for the instantaneous biological effect caused by the radiation:

$$E_{\text{eff}} = \int B(\lambda)E(\lambda) \, d\lambda. \quad [W/m^2] \quad (4)$$

The biologically effective solar radiation for the action spectra of ACGIH, CIE, DNA damage, skin cancer, photoinhibition of phytoplankton and for higher plants are shown in Figure 4(a). The effect of solar zenith angle ($\theta_s$) on the CIE weighted solar irradiance is illustrated in Figure 4(b). The not weighted solar spectrum in Figure 4(a) and the spectra of a 1000 W FEL lamp commonly used in spectroradiometer calibrations in Figure 4(b) are included for comparison. If only broadband measurements, for example erythemally weighted, are available, rough estimates for other biological effects may be obtained by using theoretical correction factors (Morys and Berger 1993, Jokela et al. 1993a).
Figure 4. With various action spectra weighted solar irradiance at solar zenith angle of 38° (a) and CIE-weighted solar spectra of zenith angles 38° and 61° (b). The not weighted solar spectrum (a) and the spectra of a 1 000 W FEL lamp (at 50 cm distance) commonly used for spectroradiometer calibrations (b) have been included for comparison.
As seen, the erythemally (CIE) weighted solar irradiance $S_h E_k$ is in its maximum at wavelengths 308 to 310 nm in the solar radiation. At shorter wavelengths the intensity of terrestrial UV radiation decreases due to strong attenuation by the ozone while at longer wavelengths the sensitivity of the skin decreases.

The integration of the equation (4) over the time from $t_1$ to $t_2$ gives the biologically effective dose $H_{\text{eff}}$ accumulated within the period $t_2 - t_1$, e.g. daily dose, yearly dose, etc.:

$$H_{\text{eff}}(t) = \int_{t_1}^{t_2} E_{\text{eff}}(t) dt = \int_{\lambda_1}^{\lambda_2} B(\lambda) E(\lambda, t) d\lambda dt \ [J/m^2]. \quad (5)$$

In solar measurements, the erythemally effective UV dose is commonly indicated in Minimum Erythema Doses [MED]. One MED is defined as a dose required to elicit just a perceptible erythema reaction on normal previously unexposed and relatively sensitive Caucasian skin. The quantity corresponds to a radiant exposure of monochromatic radiation at the maximum efficacy for erythema (around 300 nm). The value of MED depends on the skin type and there is not any standardized value for the MED and values varying from 150 to 2000 J/m² can be found in the literature (Sayre et al. 1981, Pathak and Fanselow 1983, Parrish et al. 1982, Mackenzie 1982, McKinlay and Diffey 1987) see Table I, while most commonly used values range from 200 to 300 J/m². In the studies of STUK, a value of 200 J/m² (CIE weighted) is chosen for the MED. This value is comparable with the MED of 210 J/m² specified for the Solar Light meters.
Table I. Minimum erythemal doses for different skin types.

<table>
<thead>
<tr>
<th>Skin type</th>
<th>Colour of unexposed skin</th>
<th>UV sensitivity</th>
<th>Minimum erythemal UV dose (J/m²)</th>
<th>Skin reaction when exposed to UV radiation</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>White</td>
<td>Very sensitive</td>
<td>150 - 300</td>
<td>Always burns easily, never tans</td>
</tr>
<tr>
<td>II</td>
<td>White</td>
<td>Very sensitive</td>
<td>250 - 350</td>
<td>Always burns easily, tans minimally</td>
</tr>
<tr>
<td>III</td>
<td>White</td>
<td>Sensitive</td>
<td>300 - 500</td>
<td>Burns moderately, tans gradually (light brown)</td>
</tr>
<tr>
<td>IV</td>
<td>Light brown</td>
<td>Moderately sensitive</td>
<td>450 - 600</td>
<td>Burns minimally, tans well always (moderate brown)</td>
</tr>
<tr>
<td>V</td>
<td>Brown</td>
<td>Minimally sensitive</td>
<td>600 - 1 000</td>
<td>Rarely burns, tans profusely (dark brown)</td>
</tr>
<tr>
<td>VI</td>
<td>Dark brown, black</td>
<td>Insensitive</td>
<td>1 000 - 2 000</td>
<td>Never burns, deeply pigmented (black)</td>
</tr>
</tbody>
</table>

2.3 Basic radiometry

The fundamental theory of the optical radiometry can be found elsewhere (Nicodemus et al., 1976, 1979 a,b,c and Jokela, 1992) and only brief summary is given here.

The relation of the radiometer output to the distribution of the radiation incident on it is given by the measurement equation. The relation between the incident radiation and the output signal is the instrument responsivity \( R_\phi \).
where the responsivity is generally a function of position and direction of the incoming rays on the receiving input optics as well as the wavelength of the radiation, i.e. \( R_\phi = R_\phi (x,y,\theta,\phi,\lambda) \).

It follows that the element of output signal produced by an element of incident radiant flux is given by

\[
dS = R_\phi d\Phi = (1/K_\phi)d\Phi,
\]

where \( K_\phi = 1/R_\phi \) is the calibration factor.

The general form of the measurement equation is

\[
S = \iiint_{\Delta x, \Delta y, \omega} R_\phi(x,y,\theta,\phi,\lambda)L(x,y,\theta,\phi,\lambda)\cos\theta d\omega d\Phi d\lambda,
\]

where \( x \) and \( y \) are the coordinates, on the surface, of the point of intersection with the ray, \( \theta \) and \( \phi \) are the spherical coordinates; \( \theta \) is the polar angle between the ray and the normal of the surface at the point \( x,y \) and \( \phi \) is the azimuth angle about the point \( x,y \), is obtained from the equation (7) by using the definition of the radiance \( L \),

\[
L = \frac{d^2\Phi}{dA\cos\theta d\omega},
\]

where \( dA = dx dy \). The geometry of solar measurements is illustrated in Figure 5.
Figure 5. Geometry of solar UV measurements.

2.3.1 Spectroradiometric measurements

For a spectroradiometer, the measurement equation (8) can be written in the form

\[
S(x,y,\theta,\phi,\lambda,\lambda_o) = \int \int \int R_\phi(x,y,\theta,\phi,\lambda,\lambda_o) L_\lambda(x,y,\theta,\phi,\lambda) \cos \theta d\omega d\lambda,\quad (10)
\]

where \(R_\phi\) is the flux responsivity of the spectroradiometer, when set at wavelength \(\lambda_o\) for flux element from the direction \(\theta, \phi\) at the point \(x,y\) of the receiving aperture and at wavelength \(\lambda\), \(\Delta\lambda\) is the bandwidth of the spectroradiometer, i.e. the wavelength interval over which the responsivity is not zero, \(R_\phi(\lambda,\lambda_o) \neq 0\), and \(A\) is the area of the receiving aperture. When making an assumption that the responsivity is independent of the position and direction of the incident rays, i.e. \(R_\phi(x,y,\theta,\phi,\lambda,\lambda_o) = R_\phi(\lambda,\lambda_o)\), within \(A\) and \(\omega\), when proper input optics like integrating sphere or diffuser is deployed, the equation (10) can be rewritten in the form
where \( E_\lambda \) is the spectral irradiance to be measured at the point \( x,y \) and wavelength \( \lambda \):

\[
E_\lambda(x,y,\lambda) = \frac{d\Phi_\lambda(x,y,\lambda)}{dA} = \int_{\phi} L_\lambda(x,y,\theta,\phi,\lambda)\cos\theta d\omega. \tag{12}
\]

If the radiation field is homogenous within the area of the receiving aperture, the equation (11) becomes

\[
S(\lambda_o) = A \int_{\Delta\lambda} E_\lambda(\lambda)R_\phi(\lambda_o,\lambda) d\lambda. \tag{13}
\]

The bandwidth, \( \Delta\lambda_w \), of the measurement system may be defined by the equation

\[
\Delta\lambda_w = \frac{\int_{\lambda_o} R_\phi(\lambda_o,\lambda) d\lambda}{R_\phi(\lambda_o,\lambda_o)}, \tag{14}
\]

and when making an assumption that the bandwidth is so narrow that \( E_\lambda \) is approximately constant within this bandwidth, the measurement equation for the spectral irradiance becomes

\[
E_\lambda(\lambda_o) = \frac{S}{AR_\phi(\lambda_o,\lambda_o)\Delta\lambda_w}. \tag{15}
\]

When the assumption for the narrow bandwidth is not valid, the equation (13) is presented as
where

$$z(\lambda_0 - \lambda) = \frac{\text{kr}_f(\lambda)z(\lambda_0 - \lambda)}{AR_F(\lambda_0, \lambda)}$$  \hspace{1cm}(17)$$

$z(\lambda_0 - \lambda)$ is so called slit-scattering function changing as a function of the difference of the wavelength of the flux $\lambda$, and the setting wavelength $\lambda_0$ of the monochromator, $r_f$ is so called responsivity factor, see Figure 6, and $k$ is an arbitrary factor being constant with respect of wavelength. The central portion of the slit-scattering function is determined primarily by the slit widths and dispersion of the monochromator. The wings of the function are determined primarily by internal radiation scattering.

The equation (16) is a convolution integral of $E(\lambda)r_f(\lambda)$ and $z(\lambda_0 - \lambda)$. Scanning the monochromator across a sufficiently wide range provides the peak value, $S(\lambda_0)$, of the signal. The coefficient $k$ and functions $r_f$ and $z$ are either given in technical specifications or they can be measured and the product $E(\lambda)r_f(\lambda)$ in the convolution integral can be obtained by iterative deconvolution methods.

A schematic layout of a double grating spectroradiometer is shown in Figure 7. The main parts of the spectroradiometer are input optics, wavelength selective monochromator and the detector placed at the exit slit of the monochromator.

![Figure 6. The bandwidth of a spectroradiometer.](image)
When a radiant flux with an irradiance $E$ is to be measured, the radiance, $L$, at the rear side of the diffuser is obtained as

$$L = \eta_d \frac{E}{\pi},$$  \hspace{1cm} (18)

where $\eta_d$ is the efficiency of the diffuser and $E$ is the irradiance to be measured. The radiant power entering the monochromator, $P_{in}$, can be written as

$$P_{in} = GL = \pi \sin^2 \alpha w_s h_s L,$$  \hspace{1cm} (19)

where $G = A_s \Omega$ is the geometrical extent of the monochromator, $A_s$ is the slit area, $\Omega = \pi \sin^2 \alpha$ is the projected solid angle, $\alpha = \tan^{-1}[(D_d/2)/s]$, $D_d$ is the diameter of the diffuser and $w_s$ and $h_s$ are the slit width and slit height, respectively. Further on, the radiant power entering the detector is obtained as
\[ P_{out} = \pi \sin^2 \alpha \omega \eta_s \eta_d \frac{E_\lambda}{\pi} \Delta \lambda \eta_s^2, \]  

(20)

where the \( \eta_s \) is the efficiency of the gratings, \( \Delta \lambda = w / D_L \) and \( D_L \) is the linear dispersion of the gratings.

2.3.2 Broadband measurements

Broadband measurements can be characterized basically with the same equation as the spectroradiometric measurements

\[ U(A, \omega, \Delta \lambda) = \int_{\Delta \lambda} \int_{A} \int_{\omega} R_{\Phi} L_{\lambda} \cos \theta \ d\omega \ dA \ d\lambda, \]  

(21)

where \( U \) is the reading given by the meter (e.g. dose rate in MED/h) and \( \Delta \lambda \) is the spectral pass band of the instrument where the flux response is significantly non-zero. Normally the integration is extended over the full hemisphere \( \omega = 2\pi \).

The wavelength dependent, non-uniform responsivity \( R_{\Phi} \) can be written in the form

\[ R_{\Phi} = K_f r(\lambda), \]  

(22)

where \( r(\lambda) \) is the relative spectral responsivity that is usually normalized to unity at a wavelength \( \lambda_\circ \) of maximum response, i.e. \( r(\lambda_\circ) = 1 \), and the absolute response of the instrument is obtained by using the calibration factor \( K_f \) determined at \( \lambda_\circ \).

The equation (21) becomes

\[ U(A, \omega, \Delta \lambda) = K_f \int_{\Delta \lambda} \int_{A} \int_{\omega} r(\lambda) L_{\lambda} \cos \theta \ d\omega \ dA \ d\lambda, \]  

(23)

For ideal erythemal radiation detector the spectral responsivity \( r \) should follow the CIE curve in Figure 3, i.e. \( r = r_{CIE}(\lambda) \), and exhibit no angular dependence, in which case the angular response varies according to \( \cos \theta \). However, the response of a real detector deviates from the CIE response as well as from the cosine.
response. Additionally, $K_i$ and $r$ may change as a function of temperature, humidity and radiation level.
3 RADIOMETERS USED FOR SOLAR UV RADIATION MEASUREMENTS

The radiometers used for solar UV radiation measurements can be divided in three categories based on their bandwidths. The bandwidth of the most commonly used spectroradiometers varies approximately from 0.5 to 1.5 nm and the bandwidths of so called multi-channel instruments (typically 2 to 8 bands in the UV) varies from 5 to 20 nm. The response of so called broadband radiometers covers the region approximately from 260 to 380 nm following roughly the erythemal effectiveness of the UV radiation.

3.1 Spectroradiometers

The most accurate measurements of the solar UV radiation are carried out by spectroradiometers that measure the spectral irradiance as a function of wavelength. The spectroradiometric measurement system consists typically of two main parts, the optics head and the electronic unit, and is controlled by a personal computer. Further on, the optics head consists of input optics, monochromator, detector, amplifier and steppermotor.

The most common alternatives for the input optics for solar UV measurements are teflon diffusers or teflon coated integrating spheres, which typically are designed to collect the radiation from the whole upper hemisphere. The angular response of the input optics of the commonly used solar UV spectroradiometers is designed to change as the cosine of the angle of incidence. The other features of the input optics are to depolarize the radiation and to give a homogeneous radiation field to the entrance slit of the monochromator.

In solar UV measurements, both types, single and double grating monochromators are used. The most important characteristics of the monochromator are the accuracy of the wavelength scale, throughput and stray light. The bandwidths of the commonly used spectroradiometers vary from 0.6 to 1.7 nm. The accuracy of the wavelength scale of commercial spectroradiometers is often necessary to increase by numerical methods.

A photomultiplier tube is the most commonly used detector in solar measurements, and the amplifier is typically logarithmic.
3.1.1 The reference spectroradiometer of STUK

The schematic layout of the optics head of the Optoronic 742 (denoted OL 742), a dual holographic grating spectroradiometer, is shown in Figure 8. A teflon diffuser is used as input optics, the detector is a S-20 photomultiplier tube and the amplifier is logarithmic. Control of the wavelength, high voltage power source, adjustment of the zero level of the dark current are the features of the electronics unit. The technical specifications of the OL 742 are given in Appendix A.

3.1.1.1 Calibration of spectroradiometers

Most commonly the accuracy of spectroradiometric solar UV measurements is based on calibration against 1 000 W DXW or FEL lamps, traceable to black bodies maintained at well-known national primary standards laboratories like NIST, NPL, PTB and other primary standards laboratories. The OL 742 spectroradiometer of STUK is regularly calibrated with 1 000 W quartz-halogen standard lamps traceable to the NIST in the U.S. The schematic layout of a typical spectroradiometric calibration system is presented in Figure 9 and the specifications of the equipment of STUK are presented in Table II.

![Diagram of OL 742 spectroradiometer](image)

*Figure 8. The optics head of the OL 742 spectroradiometer.*
Figure 9. The schematic layout of the calibration system

Table II. Specifications of the equipment utilized in calibration of the spectroradiometer.

<table>
<thead>
<tr>
<th>Lamps</th>
<th>Current source</th>
<th>Shunt resistor</th>
<th>Voltmeter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. 1 000 W FEL F-319 Calibration traceable to NIST via Optronic Laboratories Primary standard of STUK up to April 1994</td>
<td>Optronic 83 DS Precision Current Source</td>
<td>Cambridge Instruments 10 mΩ Manganin No L-201388 Calibration date: 931009 Calibrated by: Technical Research Centre of Finland Resistance: 9.99845 mΩ ± 0.002 %</td>
<td>Keithley 182 Sensitive Digital Voltmeter Calibration date: 931014 Calibrated by: Technical Research Centre of Finland Calibration factor: 1.000025 ± 0.001 %</td>
</tr>
<tr>
<td>2. 1 000 W FEL F-320 Secondary standard of STUK</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. 1 000 W FEL F-329 NIST lamp Primary standard of STUK after April 1994</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1) National Standards Laboratory of Finland
3.2 Robertson-Berger type broadband radiometers

Different versions of the most commonly used broadband radiometer for solar UV measurements are of the erythemally weighted RB type radiometer. Schematic diagrams of two examples of RB type sensors, Solar Light Model 500 (denoted SL 500) and Model 501 (denoted SL 501), are shown in Figure 10.

The SL 500 meter consists of a cylindrical detector head and a recorder unit. First the solar radiation incident on the Vycor dome of the SL 500 meter is filtered by a black prefilter that blocks the visible and infrared radiation. Then the remaining UV radiation is converted to visible radiation by a fluorescing phosphor layer deposited on a green post filter. The fluorescence radiation through green filter that absorbs the residual UV radiation is detected by a vacuum photodiode. The spectral response function was designed to simulate the erythemal sensitivity of the human skin. The reading of the meter is given in MED/h and the data is recorded as integrated doses of chosen intervals. Intervals of 10 and 30 minutes are commonly used. Details on the construction and design of the first generation RB meters introduced in early 1980's by Robertson (Robertson 1972) is found in Berger 1976.

Figure 10. The SL 500 (a) and SL 501 (b) detectors. The SL 500 radiometer has been modified by installing an air blow system, an additional enclosure and a temperature sensor.
The structure of the newer generation SL 501 meter, Figure 10, is basically similar with the SL 500 design. The most essential improvement in the SL 501 design is the temperature stabilization of the critical components. For the SL 501 meters a value of 210 J/m² has been specified by the manufacturer for the one MED unit, which should be accounted for by dividing the presented calibration factors by 1.05 when estimating the agreement with the calibration by the manufacturer.

3.2.2 Calibration of broadband meters

There are two approaches for the calibration of the broadband radiometers: a spectroradiometric calibration in solar radiation (Leszcynski et al. 1993) and a spectroradiometric calibration using an artificial UV radiation source, a filtered xenon lamp (Morys and Berger 1993). In both cases, the absolute calibration against primary standards is transferred to the broadband radiometers by utilizing a reference spectroradiometer as a transfer instrument. The calibration factors are obtained by comparing the dose rate readings of a broadband meter in MED/h with the CIE weighted irradiance derived from the simultaneous spectral measurement from 290 to 400 nm. For this purpose the value used for the MED has to be specified. In studies of STUK a CIE (McKinlay and Diffey 1987) weighted value of 200 J/m² is applied.

3.3 Multi-channel instruments

Multi-channel radiometers are instruments that provide spectrally resolved data, but at limited number (typically from two to eight) of wavelengths. These instruments are based on use of interference filters and solar-blind detectors. The interference filters may be accompanied with UV-passing and light blocking filters. The spectral span of the multi-channel instruments typically varies from 290 to 324 nm with eight channels with 5 nm bandwidths or from 308 to 380 nm with four channels with 10 nm bandwidths. The detector may be a photomultiplier tube, or there may be different sensors for each passband, like GaP and Si detectors. Instruments of this type are currently under development by several manufacturers and scientists.
4 SOURCES OF ERROR IN SOLAR UV RADIATION MEASUREMENTS

The most significant factors determining the absolute accuracy of the solar UV radiation measurements are the uncertainty of primary and secondary standards, errors in calibration, non-ideal angular and spectral responses of the instruments, inaccuracy of the wavelength scale and non-ideal slit function of spectroradiometers, temperature sensitivity of the instruments and stray light (Leszczynski et al. 1994a). Besides these error components, also the effect of polarization and homogeneity of the radiation and non-linearity of the detectors should be estimated. In this chapter, the most significant sources of error and methods for error reduction are discussed. Except the uncertainty associated with primary standards which doesn't depend on the type of radiometer, the other sources of errors are introduced separately for the spectroradiometers and broadband radiometers.

4.1 Primary standards

The absolute accuracy of the precision measurements of solar UV radiation is ultimately limited by the absolute accuracy of the UV irradiance normals. The typical uncertainties (1σ) of irradiance in the UV region for the commonly used transfer standards, 1000 W FEL or DXW lamps, as specified by these laboratories vary from ±1.1 to 3.5 % at 280 nm to ±0.5 to 2.3 % at 400 nm (Walker et al., 1991). However, it should be noted that the results from the recent intercomparison of halogen lamp measurements between the national standards laboratories shown in Figure 11 indicate differences even greater than 4 % in the UV range (Walker et al., 1991).

To improve the international uniformity and traceability of radiometric scales in UV, a Working Group on Air-Ultraviolet Spectral Radiometry was established within the Comité Consultatif de Photométrie (CCPR) of the Bureau International des Poids et Mesures (BIPM) in 1990 (Tegeler 1993, Anevsky et al. 1992). Among others, the recommendations of the working goup for the national metrology laboratories include to initiate or continue the following activities: 1) Improvement of uncertainties associated with black-bodies, 2) Development of cryogenic radiometers, 3) Comparison of the three radiometric scales in the air UV (black-body radiator, electron storage ring, electrical substitution radiometer) with uncertainties below 0.5 % in order to establish a unified, internationally accepted radiometric scale, 4) development of new transfer source standards and 5)

One possible way to increase the uncertainty associated with primary standards is to verify the uncertainty of the source based calibration with cryogenic detector based standards. The cryogenic electrical substitution radiometers, the accuracy of which is based on equivalence of the electrical and optical heating power, are the most accurate primary radiometric standards with uncertainties of less than 0.01 % (Quinn and Martin 1991, Anevsky et al. 1992, Varpula et al. 1989). By utilizing a UV laser the cryogenic radiometer can be used to determine the absolute response of the transfer standard, e.g. a pyroelectric Si detector. The spectral responsivity of the transfer standard can be measured by utilizing an irradiance monochromator. Finally, the absolutely calibrated transfer standard can be used to measure the irradiance over a known bandpass of the standard lamp. This result can be compared with a result derived from the measurement of the same bandpass with a spectroradiometer that has been calibrated against lamp standard. Agreement of the two methods would increase the confidence on the lamp based calibration. The uncertainty related to the detector based calibration is reported to be within ±1 % (Jauniskis et al. 1992).

Figure 11. Results of the CCPR intercomparison of spectral irradiance measurements by national laboratories (Walker et al. 1991).
4.2 Spectroradiometric measurements

4.2.1 Calibration

Besides the uncertainty of the standard lamp, the overall uncertainty of the calibration of a spectroradiometer is increased - typically by approximately ±2% - by the uncertainty of alignment of the calibration system, the accuracy of the current source of the lamp, the accuracy of the shunt resistor and the accuracy of the voltmeter used to monitor the current. The error of 0.1% in the current setting causes an uncertainty of 0.9% in the spectral irradiance at 300 nm of halogen standards. Also, the temperature of the laboratory may become a source of error, if it is high or if there occur rapid changes in the temperature. It is often necessary to use air conditioner to cool down the laboratory, but air currents around the lamp should be avoided. The highest accuracy for the alignment is obtained by utilizing specially designed alignment systems and an alignment laser.

4.2.2 Angular response

In ideal case, the angular response of a UV spectroradiometer should change as the cosine of the angle of the incidence and not have any azimuthal dependence, but this is not achieved in practice. The error caused by the non-ideal cosine response is not significant when calibrating with the point source at normal incidence. Instead, in solar measurements, when the input optics of the instrument receives the direct radiation from the sun at varying elevation angles as well as the diffuse component from the whole sky, the importance of the angular response becomes clear. At zenith angles greater than 60° the deviation from the cosine response is typically more than 10%. The error caused by the non-ideal cosine response can be minimized by determining a correction factor based on the actual measured angular response of the instrument and some assumptions on the distribution of the UV radiation on the sky (Grainger et al. 1993, Seckmeyer and Bernard 1993), as will be shown in chapter 6.1.1. By using a correction factor the uncertainty due to the non-ideal cosine response can be decreased down to level of approximately from ±3 to ±5% (Seckmeyer and Bernhard 1993, Leszczynski et al. 1993).

4.2.3 Wavelength scale

In solar measurements, the requirement for the accuracy of the wavelength scale is stringent. Due to the steep increase of the spectrum from 290 to 310 nm, the
maximum error should be less than 0.1 nm. Even the shift of 0.1 nm of the wavelength scale may contribute an error of 5 to 10% at 300 nm, and a shift of 0.25 nm an error of approximately 7% to the CIE weighted solar irradiance of the range 290 to 400 nm. In the laboratory calibrations the requirements are much less stringent due to the smooth increase of the spectral irradiance of calibration lamps (see Figure 4(b), page 17).

The inaccuracy of the wavelength scale of a commercial spectroradiometer may be as high as 0.5 nm, which may still be increased by temperature effects. Based on measurements in STUK, the temperature sensitivity of the wavelength scale of the Optronic 742 spectroradiometer was found to be 0.034 nm/°C. A significant improvement down to wavelength accuracy of 0.1 nm can be obtained by measuring the 253.65 nm mercury line at the beginning of every spectrum and correcting the results numerically for the measured shift. Another approach is to use the Fraunhofer lines in the solar spectrum for verifying the wavelength accuracy (Huber et al. 1993).

4.2.4 Temperature sensitivity

In the case of many spectroradiometers, it is crucial to evaluate the temperature sensitivity of the instrument. According to the temperature test of the Optronic 742 spectroradiometer carried out by STUK, the difference of ±5 °C in the temperature of the optics head between the calibration and measurement causes an error of ±5% for the CIE weighted solar measurement. The temperature effect can be minimized by stabilizing the temperature of the optics head as well as possible. The residual temperature effect can be further minimized by determining the temperature coefficient of the instrument and correcting the results on the basis of the difference between the recorded calibration and measurement temperatures. These problems are avoided when using the new generation temperature stabilized spectroradiometers.

4.2.5 Stray radiation

Stray radiation is unwanted radiation reaching the detector along with the desired wavelengths. The radiation may leak through the monochromator due to scattering and reflections of the unwanted portions of the spectrum inside the casing. All grating monochromators pass also radiation of higher orders of the set wavelength. The stray light is a significant source of error in the spectral regions where the source is relatively weak, the grating is relatively inefficient, the transmission of the optical system is low or the detector sensitivity is low. When measuring the
solar radiation where the spectrum increases three orders of magnitude in the range of 290 to 310 nm, the shortest wavelength UV measurements may easily be distorted by stray radiation caused by the longer wavelengths. The scanning of the spectroradiometer over a monochromatic spectral line from a low pressure mercury lamp or an UV laser gives the information on the stray light arising due to non-ideal slit function when measuring a broadband spectrum. The error in solar spectrum measurements due to non-ideal slit function can be estimated by convoluting the solar spectrum with the measured slit function and comparing the result with a convolution based on rectangular slit function. The ways to minimize the effect of stray light are to use double-grating monochromators or cut-off filters and use a deconvolution algorithm.

Besides the stray radiation caused by the imperfect or dirty optics, stray radiation may be originated from the radiation source itself. For example, when calibrating, the reflections from the neighbouring surfaces may cause error unless a proper baffling is applied.

The appearance of the stray light in the measured spectra can be estimated by using a filter, the cut-off wavelength of which is just longer than the wavelength to be measured. If the measurement result at the cut-off region deviates from zero, it is an indication of imperfect stray light rejection and the stray light should be reduced from the measured spectra.

4.3 Broadband measurements

In case of the broadband radiometers, the ultimate limit of the absolute uncertainty set by the primary standards is further increased by the uncertainty of the spectroradiometer that serves as a transfer standard for the broadband meters.

The well-known systematic errors associated with the measurements with the erythemally weighted radiometers are the deviation of the angular response from the ideal cosine response and the deviation of the spectral response from the CIE erythemal action spectrum, temperature sensitivity and the shift of the spectral response towards longer wavelengths with increasing temperatures (Johnsen and Moan, 1991, Leszczynski et al. 1993, Dichter et al. 1992, Blumthaler and Ambach 1986).

Based solely on the angular responses, however, not any straightforward conclusion can be drawn what the effect of these non-ideal cosine responses on the solar measurements would be, because simultaneously with the radiation geometry also the spectrum is changing. In the ideal case, the meter response
geometry also the spectrum is changing. In the ideal case, the meter response should exhibit no angular dependence but to vary according to the ideal cosine function and the spectral response of the erythemal radiometer should follow the CIE action spectrum. In practice, however, the non-ideal spectral response may have a compensating effect on the poor cosine response (Leszczynski et al. 1993).

The two last error components listed above associated with temperature effects apply only to the older generation instruments that are not temperature stabilized. Other uncertainty factors include such as long-term stability, linearity, surface homogenity of the input optics, sensitivity to polarized radiation, etc.

An uncertainty level comparable with many spectroradiometric measurements is achievable for the broadband measurements by thorough characterization of the instruments in respect of the known sources of error, numerical error corrections stabilization against environmental factors and carrying out a sufficient number of spectroradiometric calibrations in solar radiation.
5 CHARACTERIZATION OF THE UV RADIOMETERS BY STUK

To increase the absolute accuracy of the solar UV measurements, the OL 742 spectroradiometer and the SL 500 and SL 501 radiometers have been characterized by measuring their angular responses, the OL 742 and the SL 500 by measuring their temperature sensitivities, the OL 742 by measuring its slit function and the SL 500 and 501 meters by measuring their spectral responsivities. Because of the complexity of the estimation of the performance of the broadband radiometers in solar radiation only on the basis of the knowledge of the separate characteristics, the characterization of these instruments is completed with the spectroradiometric calibrations in solar radiation. This chapter contains the materials and methods utilized together with the results obtained.

5.1 The spectroradiometer of STUK

5.1.1 Cosine response

The cosine response of the OL 742 spectroradiometer with two different input optics, a teflon diffuser and a teflon coated integrating sphere, was measured utilizing a 200 W halogen lamp as a radiation source. The lamp was operated with a high precision current source OL 65. The optics head was placed at the centre of a turntable at the distance of 50 cm from the lamp and the radiation field was limited with two baffles. The cosine response was measured at the wavelength 310 nm, the most effective wavelength in the solar spectrum. The deviation from the ideal cosine response for both type of input optics is shown in Figure 12.

The cosine performance of the integrating sphere was not found to be superior to that of the diffuser. In both cases the relative angular response decreases more steeply than the ideal cosine response with the increasing angle of incidence. This does not distort the measurements if the radiation reaches the diffuser in very small angles of incidence. In solar UV measurements the spectral irradiance values are too low because the radiation is distributed over the whole sky. For comparison, the deviation of the angular responses of SL 500 and SL 501 broadband meters from the ideal cosine response have been included in the Figure 12, too.
5.1.2 Slit function

The slit function of the OL 742 was measured by using the 253.65, 296.73 and 365.02 nm mercury lines. There was not any difference in the slit functions at the different wavelengths. The result obtained at 253.65 nm is shown in Figure 13. The measurement was repeated five times and the temperature of the laboratory was 22 ±1 °C. The obtained full width at half maximum (FWHM) is 1.7 nm, which may be compared with the 1.5 nm specified by the manufacturer.

Figure 12. The measured cosine responses of the spectroradiometer Optronic 742 equipped with the teflon diffuser and integrating sphere. The measured cosine responses of the broadband meters have been included for comparison.

Figure 13. The slit function of the OL 742 spectroradiometer of STUK.
5.1.3 Temperature sensitivity

Because there was not any temperature control system for the optics head of the OL 742, a thermocouple type temperature sensor was installed inside the monochromator in close proximity of the photomultiplier tube, and the temperature sensitivity of the optics head was tested by utilizing a climate chamber. As in cosine response measurements, a 200 W halogen lamp was used as an irradiation source operated with the OL 65 constant current source. The temperature tests carried out for the temperature range from 16 to 38 °C at approximately five degree intervals, and the measurements were repeated three times. The wavelength shift due to the temperature change was estimated by measuring the 253.65 nm mercury line in connection of every halogen lamp measurement. The temperature sensitivity of 0.034 nm/°C was obtained for the wavelength scale. After a numerical correction of the shift of the wavelength scale the residual temperature effect on the measured irradiances was estimated. As a result, a temperature correction equation

\[ E_T = [1 + K_{\Delta T}(T-T_0)] E_o \]  

was obtained, where the experimental coefficient \( K_{\Delta T} = 0.015 \, ^\circ\text{C}^{-1} \) and \( E_T \) and \( E_o \) are the spectral irradiances at temperature \( T \) and reference temperature \( T_0 \), respectively. The temperature sensitivity didn't show spectral dependence in the wavelength range of 300 to 400 nm.

5.2 The Solar Light Model 500, 501 and 501A radiometers

The first preliminary tests for the SL 500 meters were carried out in STUK in 1990 and the first three network instruments of FMI were installed in 1991. Further tests have been performed since summer 1992 when the meters were taken from the measurement sites for installation of temperature sensors and other modifications (Leszczynski et al. 1993). Besides the here mentioned three meters of the FMI, one additional SL 500 unit of the STUK has been evaluated. In 1992 STUK tested one SL 501 meter, in spring 1993 preliminary tests for another unit of the SL 501 meter were performed and in 1994 one unit of model 501A was tested in the laboratory. Further five SL 501A units and one SL 501 unit are to be tested in 1994.
5.2.1 Spectral response

The radiation source used for the spectral response measurements was an irradiance monocromator system consisting of a 1000 W xenon lamp Oriel 6271 together with a monochromator Oriel 77200. To measure the relative spectral responsivity of the broadband radiometers, they were placed at various distances from the output slit of the monochromator so that the detector area was covered with the radiation field. Varying slit widths were used and the measurements were performed at 2 to 10 nm intervals depending on the wavelength. The stability of the irradiance monochromator was monitored with a previously calibrated thermopile detector Oriel 71776 with fused silica window. The temperature during the measurements was 21 ±1 °C. At wavelengths 350 to 400 nm, when a broad slit width was necessary due to the low response of the SL meters, a band pass coloured glass filter (Oriel 51715) was used to cut off the wavelengths shorter than 320 nm. To correct the distortion due to the finite bandwidths an iterative deconvolution technique (Nicodemus 1979b) was used. Deconvoluted spectra were in good agreement with the non-corrected spectra measured with narrow slit widths of one and two nanometers.

The measured spectral response functions for all the test units are presented in Figure 14. The differences between all the individual responses are small in the critical band from 300 nm to 320 nm. Up to 320 nm there is a good agreement with the spectral responsivities given by the manufacturer, too. When compared with the SL 500 meter the spectral response of the SL 501 has a slightly better agreement with the CIE erythema action spectrum.

Additionally, the preliminary tests on the temperature dependence of the spectral responsivity function have been carried out. The results obtained support the reported findings of the shift of the response towards longer wavelengths with the increasing temperatures (Berger 1976, Johnsen and Moan 1991). Thus the spectral responsivity varies as a function of the elevation angle, which should be noted.
Figure 14. Relative spectral responsivities of the tested SL 500 and SL 501 meters together with the CIE action spectrum. The temperature of the laboratory was 21 ±1 °C.

The effect of spectral responsivity deviations from the CIE curve has been examined theoretically by comparing the results obtained by weighting different solar spectra with the measured spectral responsivities. Before the comparison, a high elevation solar spectrum was chosen for a reference and the spectrum was convolved with the CIE action spectrum. The SL response weighted irradiances were artificially calibrated to agree with this CIE weighted irradiance of the high sun. The effect on calibration factors caused by the differences between the spectral responsivities of one SL 501 and four SL 500 units within the elevations from the reference angle of 52° down to 32.6° has been shown to remain within 2.5 % from the unity (Leszcynski et al. 1993). The agreement of the spectral responsivities with the CIE action spectrum is fairly satisfactory. The spectral responsivities of the SL 500 and SL 501 V.1 meters of the STUK were measured in summer 1992 and in May 1993. No detectable changes had occured after the first measurement.

5.2.2 Cosine response

A metal halide sun lamp Philips HPA 400 W was used for the cosine response evaluations of the broadband meters. The spectrum of the sun lamp approximates the solar UV radiation of the elevation angle of 53°, which is the highest elevation at the Helsinki latitude. The meters were placed at the centre of a turntable specially built for these measurements at the distance of approximately 50 cm from the sun lamp. The field of view of the meters was limited with a black
baffle. During the measurements the temperature of the green filter of the SL 500 detector remained stable 25 °C and also the temperature of the SL 501 was stabilized at 25 °C. The turntable was turned at steps of five degrees.

The deviations from the ideal cosine response for the broadband radiometers was shown in Figure 12. The maximum deviation from the ideal cosine response remains within ±15 % when the angle of incidence (zenith angle) is within 60 degrees. The SL 500 as well as the Version 1 of the SL 501 are seen to overestimate the cosine response approximately from the angle of ±30° to 75...80°.

5.2.3 Temperature sensitivity

Temperature tests were carried out for the modified SL 500 meter of the STUK. The metal halide sun lamp Philips HPA 400 W was utilized during the temperature tests performed in a climate chamber. The test detector was placed in the climate chamber and irradiated with a sun lamp. The stability of the irradiation field was monitored with a temperature stabilized SL 501 radiometer.

The results from the temperature tests from -19 to 45 °C normalized to 25 °C are shown in Figure 15. The temperature coefficients obtained are 0.80, 0.81 and 0.76 %/°C based on the temperature measurements of the phosphor, detector body and air, respectively. These figures agree well with the first test results from 1991 (Jokela et al. 1991) as well as with the Austrian and Norwegian findings (Blumthaler and Ambach 1986, Johnsen and Moan 1991).

In reference Leszczynski et al. 1993, the results based on SL 500 measurements on a cold and sunny day in February and a warm and sunny day in April are compared. The daily total doses and maximum values of the recorded temperatures are summarized in Table III. Three alternatives for the daily totals are given: the uncorrected detector output, the output corrected by using the ambient air temperature, and the output corrected by using the measured green filter temperature. A thermal correction coefficient of 0.7 %/°C based on previous tests (Jokela et al. 1991) was used.
Figure 15. Temperature sensitivity of the SL 500 meter based on the temperature measurements of the green filter (below the phosphor layer), of the detector body and of air.

Table III. Recorded daily total doses on cold and warm spring days based on different ways of temperature correction.

<table>
<thead>
<tr>
<th></th>
<th>21 Feb</th>
<th>30 Apr</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_{GF, max} [°C]</td>
<td>0</td>
<td>+40</td>
</tr>
<tr>
<td>D_{TOT(T_{GF})} [MED]</td>
<td>1.23</td>
<td>10.75</td>
</tr>
<tr>
<td>T_{air, max} [°C]</td>
<td>-8</td>
<td>+18</td>
</tr>
<tr>
<td>D_{TOT(T_{air})} [MED]</td>
<td>1.32</td>
<td>12.02</td>
</tr>
<tr>
<td>D_{TOT, raw}</td>
<td>1.04</td>
<td>11.18</td>
</tr>
</tbody>
</table>

1) Maximum temperature of the green filter
2) Daily total dose normalized to 25 °C on the basis of the green filter temperature
3) Maximum air temperature
4) Daily total dose normalized to 25 °C on the basis of the ambient air temperature
5) Daily total dose based on raw data without temperature normalization
The deviation of the with respect of air temperature corrected result from the with respect to the green filter temperature corrected daily total is +7 and +12 % for the cold and warm day, respectively. The deviation of the raw values from the according to the green filter temperature corrected values are -15 % (February) and 7 % (April). Despite of the possibility that the air and green filter temperatures underestimate the phosphor temperature, these results indicate considerable improvement of the measurement accuracy as a result of temperature correction.

5.2.4 Calibration of broadband meters

The spectroradiometric calibrations of the broadband meters in solar radiation were carried out in Helsinki city area (60.2°N, 25.0°E) on a roof of a high building where the sky is almost unobstructed. During the calibrations the test detectors and the spectroradiometer were directed towards the zenith. The temperatures of the SL 500 detectors were monitored and the dose rates were normalized to 25 °C, which was also the stabilization temperature of the SL 501 meters. The optics head of the spectroradiometer was kept as close as possible to the calibration temperature and the accuracy of the wavelength scale was controlled by measuring the 253.65 nm mercury line at the beginning of every solar spectrum. Additionally, the effect of residual temperature difference was corrected by using a correction equation (24) based on the earlier temperature tests.

During the spectral scan from 290 to 400 nm the instantaneous readings of all the broadband radiometers were simultaneously recorded. From the spectroradiometric measurements the dose rate value was derived by computing the CIE weighted irradiance in the range of 290 to 400 nm and converting the irradiance to dose rate weighted (1 MED/h = 200 J/m²h = 0.0555 W/m²). For each broadband meter the scan average of the readings was calculated and compared with the dose rate values based on the spectroradiometric measurements.

The solar calibrations of the SL 500 and SL 501 meters of the STUK analyzed in this study were performed on sunny days during May through August in 1992 and during April, May and July in 1993 at solar elevation angles from 18° to 52°. The number of overall spectral calibrations of the SL 501 and SL 500 meters was 92 and 99, respectively. Some spectral calibrations, not included in the basic calibration results, were performed on cloudy days, too.

The clear sky calibration factors for the SL 500 and SL 501 V.1 meters are shown in Figure 16. The calibration factors of the SL 500 meter are normalized to the
25 °C based on the green filter temperatures. The obtained absolute average calibration factors are 1.15 and 0.93 for the SL 500 and SL 501 V.1 meters of the STUK, respectively.

The present calibration of the three SL 500 meters of the FMI is based on the intercomparison with the OL 742 spectroradiometer of STUK in 1993, whereas the first solar calibration of the instruments in 1992 was based on comparison only with the spectroradiometrically calibrated SL 500 meter of the STUK. The obtained calibration factors of the three SL 500 meters of the FMI were 1.17 and 1.13, 1.14 and 1.06, and 1.07 and 1.11 in 1992 and 1993, respectively. The SL 501 V.3 was calibrated only in 1993 and the obtained calibration factor was 0.98. According to the preliminary results the calibration factors obtained on cloudy weather fall within the clear day values.

Figure 16. Calibration factors for the SL 500 and SL 501 meters based on spectroradiometric calibration measurements on clear days at varying elevation angles. The SL 500 results have been normalized to 25 °C based on the green filter temperature and a temperature coefficient of 0.8 %/°C. The SL 501 V.1 meter was stabilized to 25 °C.
After dividing by the factor of 1.05 due to the different definitions for the MED, the calibration factors obtained by STUK may be compared with the manufacturer calibration (calibration factor unity). The difference of approximately 12 % between the solar calibrations by the STUK and laboratory calibrations by the manufacturer might be explained by the difficulty of simulating the geometry of the solar radiation measurements in a laboratory.

Finally, Figure 17 shows a comparison of the results obtained with the two versions of the SL 501 meter, versions V.3 and V.1. The meter readings were normalized to unity at noon. At low elevation angles a significant difference can be seen. The sensitivity of the Version 1 meter increases due to the increasing angular response, which may compensate the opposite effect associated with the shift of the spectrum towards longer wavelengths.

![Figure 17](image.png)

**Figure 17.** The ratio of the calibration factor of the SL 501 V.3 to the SL 501 V.1 as a function of the elevation angle.
6 ERROR REDUCTION OF THE MEASUREMENTS BY STUK

6.1 Spectroradiometric measurements

Based on the characterization measurements of the OL 742 spectroradiometer described in Chapter 5.1, the basic accuracy of the spectroradiometer has been improved in respect of non-ideal cosine response, shift of the wavelength scale and in respect of temperature sensitivity as follows.

6.1.1 Correction of the cosine error

Since the non-ideal cosine response is in many cases the most significant source of error in solar UV radiation measurements, the theory for the correction is presented briefly.

Based on the measurement equation (8) and using the relation \( d\omega = \sin\theta d\theta d\phi \), the signal of any detector produced by solar UV radiation can be expressed as

\[
S \propto \int_{\lambda_1}^{\lambda_2} \int_0^{2\pi} \int_0^\pi R(\theta, \phi, \lambda) L(\theta, \phi, \lambda) \sin\theta d\theta d\phi \, d\lambda,
\]

(25)

where \( L(\lambda) \) is the radiance from the Sun and the sky, \( \theta \) is the zenith angle and \( \phi \) the azimuthal angle (see Figure 5, page 21, for the geometry). Based on experimental evidence, the zenith angle and spectral responsivities are assumed to be separable and there has been expected to be no azimuthal angular dependence, i.e.

\[
R(\lambda, \theta, \phi) = K_r A(\theta) r(\lambda) = K_1 C(\theta) \cos \theta r(\lambda),
\]

(26)

where the \( A(\theta) \) and \( C(\theta) \) are the actual and relative cosine responses of the instrument, respectively and \( K_r \) is calibration factor. In clear sky conditions the radiance \( L(\lambda) \) can be split into direct component from the Sun, \( L_D \), and diffuse component scattered from the sky, \( L_s \). With all these assumptions and combining equations (25) and (26) we get
The direct component of solar radiation from direction \( \theta, \phi \), can be expressed as

\[ L_D(\lambda, \theta, \phi) = \pi L_D(\lambda, \theta, \phi) \delta(\theta - \theta_o) \delta(\phi - \phi_o), \quad (28) \]

where \( \delta \) is the Dirac delta function, and the scattered diffuse component may be assumed to be isotropically distributed having neither azimuthal nor zenith angle dependence. By combining the equations (27) and (28) we obtain

\[
S = K_1 \int_{0}^{\lambda_2} \int_{0}^{2\pi} r(\lambda)A(\theta)[L_S(\lambda, \theta, \phi) + L_D(\lambda, \theta, \phi)] \sin \theta \, \phi \, d\lambda.
\]

(27)

The direct component of solar radiation from direction \( \theta, \phi \), can be expressed as

\[
L_D(\lambda, \theta, \phi) = \pi L_D(\lambda, \theta, \phi) \delta(\theta - \theta_o) \delta(\phi - \phi_o),
\]

where \( \delta \) is the Dirac delta function, and the scattered diffuse component may be assumed to be isotropically distributed having neither azimuthal nor zenith angle dependence. By combining the equations (27) and (28) we obtain

\[
S = K_1 \int_{0}^{\lambda_2} \int_{0}^{2\pi} r(\lambda)A(\theta) \sin \theta \, d\theta \, d\phi \int_{\lambda_1}^{\lambda_2} r(\lambda)E_S(\lambda) d\lambda + A(\theta_o) \int_{\lambda_1}^{\lambda_2} r(\lambda)E_D(\lambda) d\lambda
\]

(29)

and by introducing new variables

\[
P_D = \int_{\lambda_1}^{\lambda_2} r(\lambda)E_D(\lambda) d\lambda,
\]

(30)

\[
P_S = \int_{\lambda_1}^{\lambda_2} r(\lambda)E_S(\lambda) d\lambda
\]

(31)

and

\[
D = \frac{1}{\pi} \int_{0}^{2\pi} \int_{0}^{\pi} A(\theta) \sin(\theta) d\theta d\phi
\]

(32)
the equation (29) may be rewritten:

\[ S = \pi K_1 [DP_s + \cos(\theta_0)P_D]. \]  \hspace{1cm} (33)

In ideal case \( A(\theta) \) changes as \( \cos(\theta) \), and \( D = 1 \)

\[ S_i = \pi K_1 [P_s + \cos(\theta_0)P_D]. \]  \hspace{1cm} (34)

The correction factor for the non-ideal cosine response is obtained as

\[ K = \frac{S_i}{S} = \frac{P_s + \cos(\theta_0)P_D}{DP_s + A(\theta_0)P_D}. \]  \hspace{1cm} (35)

Because of assumption that the angular response doesn't have azimuthal dependence, a simplified expression for variable \( D \) is obtained:

\[ D = \frac{1}{\pi} \int_0^{\pi/2} \int_0^{2\pi} A(\theta) \sin(\theta) d\theta d\varphi = 2 \int_0^{\pi/2} A(\theta) \sin(\theta) d\theta. \]  \hspace{1cm} (36)

The calculation of the variable \( D \) may be simplified by approximation of the measured angular response by a polynomial function

\[ A(\theta) = a_0 + a_1 \theta + a_2 \theta^2 + a_3 \theta^3 \ldots \]  \hspace{1cm} (37)

Based on assumptions for the relation of diffuse and direct components at different elevation angles the following correction factors were obtained

<table>
<thead>
<tr>
<th>Elevation angle [deg]</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct radiation component [%]</td>
<td>0</td>
<td>10</td>
<td>20</td>
<td>30</td>
<td>40</td>
</tr>
<tr>
<td>Correction factor for OL 742</td>
<td>1.1063</td>
<td>1.1096</td>
<td>1.1088</td>
<td>1.1008</td>
<td>1.0836</td>
</tr>
</tbody>
</table>

To minimize the cosine error down to \( \pm 5\% \) the spectroradiometric data is corrected with a factor of 1.10.
6.1.2 Correction of the shift of the wavelength scale

During every scan of the spectroradiometer the shift of the wavelength scale is measured and corrected by using the 253.65 nm characteristic line of a low pressure mercury lamp. The correction is based on fitting the measured line to the reference peak. A wavelength accuracy of ±0.15 nm has been achieved in the UV range, which is a clear improvement when compared to the ±0.5 nm specified by the manufacturer. The present uncertainty (2σ) associated with the shift of the wavelength scale is estimated to be ±3%.

6.1.3 Correction of the temperature effects

The internal temperature of the optics head is recorded during all the measurements and the results are corrected according to the equation (24) with respect to the temperature difference between the calibration and measurement temperatures. During outdoor solar measurements the temperature performance is also improved by placing the optics head in a styrofoam box the temperature of which is kept as close as possible to the calibration temperature. The uncertainty related to the temperature difference between the calibration and the test measurements is estimated to be ±3%.

6.1.4 The overall error budget

The overall uncertainty (2σ) of the solar UV radiation measurements with the OL 742 spectroradiometer of STUK has been estimated to be ±8% (WECC 1990). The error budget is presented in Table IV. By combining the specified uncertainties associated with the calibration lamp, ±2%, and the alignment, ±3%, in quadrature, an estimate of 3.6% is obtained for the laboratory calibration of the spectroradiometer.
Table IV. The uncertainty (2 sigma) of solar UV measurements with the OL 742 spectroradiometer at 310 nm.

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration</td>
<td></td>
</tr>
<tr>
<td>lamp</td>
<td>±2</td>
</tr>
<tr>
<td>alignment</td>
<td>±3</td>
</tr>
<tr>
<td>Measurements</td>
<td></td>
</tr>
<tr>
<td>shift of the wavelength scale</td>
<td>±3</td>
</tr>
<tr>
<td>cosine response</td>
<td>±5</td>
</tr>
<tr>
<td>azimuthal response</td>
<td>±1</td>
</tr>
<tr>
<td>temperature</td>
<td>±3</td>
</tr>
<tr>
<td>slit function</td>
<td>±2</td>
</tr>
<tr>
<td>stray light</td>
<td>&lt;±1</td>
</tr>
<tr>
<td>non-linearity of the detector</td>
<td>≤±1</td>
</tr>
<tr>
<td>random</td>
<td>±3</td>
</tr>
<tr>
<td><strong>Overall uncertainty</strong></td>
<td><strong>±8 %</strong></td>
</tr>
</tbody>
</table>

6.2 Broadband measurements

6.2.1 Temperature sensitivity

To eliminate the errors caused by the temperature effects, the three SL 500 meters of the FMI and the one unit of the STUK have been modified by FMI by installing a temperature sensor at the underside of the green filter (Leszczynski et al. 1993) to enable correction of the measured dose rates with respect to temperature. The temperature of the green filter is assumed to follow the phosphor. The FMI instruments were modified still by including an additional casing around the detector body and by installing a small fan to keep the dome surface temperature above the dew point of the ambient air (see Fig. 10, p. 30). Since the SL 500 unit of the STUK is used only for calibration purposes during warm weathers no air blow arrangements were needed. The more detailed description of the modifications can be found in Leszczynski et al. 1993.
6.2.2 Overall uncertainty

The basic spectroradiometric uncertainty is ±8 % of the OL 742 of STUK as stated previously, and the uncertainties associated with the calibration of the broadband meters can be estimated with the aid of Figure 16. In the case of SL 501 meter, the random variation is seen to be approximately ±8 %, and an estimate of ±11 % for the overall calibration uncertainty is obtained by calculating the square root of the sum of the squares of these uncertainty components. For the SL 500 meters the random variation is ±10 % and the systematic uncertainty component due to the temperature sensitivity is about ±10 % resulting in the overall uncertainty of ±14 % for the calibration results corrected with respect to the green filter temperature. The uncertainty of the older generation, not temperature stabilized, Solar Light model 500 is estimated to be ±19 %, (Leszczynski et al. 1993).
7 SOLAR UV RADIATION MEASUREMENT NETWORKS

Numerous efforts for monitoring the solar UV radiation have been carried out throughout the world, but still the geographical coverage and time span of these measurements is insufficient for constructing a global climatology, or to estimate long-term trends in the UV level. Moreover, the quality control (QC) and quality assurance (QA) procedures have been considered insufficient, the instruments have not been thoroughly characterized prior to deployment for later evaluation on any instrumental drifts and there exists questions about the calibration of the instruments (UNEP 1991, IARC 1992, Driscoll 1992, Frederick and Weatherhead 1992, Kennedy and Sharp 1992).

The most comprehensive series of UVB measurements from 1974 to 1985 have been carried out with RB meters forming a network of 25 U.S. stations and 11 non-U.S. stations. An analysis of the data of eight of the U.S. network stations by Scotto et al. revealed declines in irradiance at all the stations included in the study. The decline in annual integrated RB meter signals varied between 0.5 and 1.1 % (Scotto et al. 1988). This result was contradictory to expectations based on the detected decline in the total ozone over this time period. The problems in the long-term calibration and changes in cloudiness, in aerosol content of the atmosphere and local pollution have been suggested for the reasons (Grant 1988, Freuerick et al. 1991, UNEP 1991, Kennedy and Sharp 1992, Frederick and Weatherhead 1992, WMO 1992).

The RB data of the period from 1981 to 1989 from the Swiss Alps indicated an annual increase of 0.7 ± 0.2 % (Blumthaler and Ambach 1990). In Moscow, based also on the RB measurements a decrease of 12 % in UV radiation was detected within the period from 1968 to 1983, leading to the annual decrease of 0.8 % (UNEP 1991).

The time span of the spectral UV measurements is too short to extract statistically significant UV distribution and trend information.

In Appendix B, a list of reported solar UV measurement sites and examples of utilized instrumentation is presented. It includes 81 broadband meters and 35 spectroradiometers of which 14 instruments are specified as Brewers. However, based on the information from the instrument manufacturers, the overall number only of the broadband Solar Light instruments is 181 (personal communication to Marian Morys, SolarLight Co., Inc.) and the Brewer spectroradiometers is 100 (personal communication to Ken Lamb, Sci-Tech Instruments, Inc.) indicating that
the list covers only a fraction of the number of the instruments used for solar UV monitoring. Based on the above presented numbers, the estimates of 150 for the spectroradiometers and more than 200 for the broadband meters are obtained.

Although the UV radiation measurements are carried out in various sites worldwide, most of the results are not comparable due to the diversity of the calibration and measurement procedures.
8 SOLAR UV RADIOMETER INTERCOMPARISONS

The only way to verify that the spectroradiometric scales in the solar UV measurements are uniform is to arrange large scale intercomparisons of the instruments. However, so far only three international intercomparisons have been reported (Gardiner and Kirsch 1992, Gardiner et al. 1993, Gardiner and Kirsch 1993, McKenzie et al. 1993) and reports from the third European intercomparison in 1993 and the Nordic intercomparison in 1993 are expected to be published in 1994 (NOGIC-93 1994). Besides these intercomparisons, there have been carried out several small scale intercomparisons, specially in the U.S. but also elsewhere, e.g. the first preliminary Nordic intercomparison was arranged in 1991 in Norrköping, Sweden (Josefsson 1991). In this chapter, a brief summary of the reported European and New Zealand intercomparisons and the Nordic (1993) intercomparison will be given. The results of the Nordic intercomparison are available due to the participation of STUK in this intercomparison.

8.1 The first European intercomparison of spectroradiometers

The first reported European intercomparison (Gardiner and Kirsch 1992, Gardiner et al. 1993) of spectroradiometers was arranged in 1991 as a part of a European Community project aimed at establishing the criteria for a network of ultraviolet radiometers to measure the variations of UVB irradiance throughout Europe. Six different types of spectroradiometers from Austria (two instruments), Belgium, Great Britain (GB), Greece (GR) and Norway were present at the intercomparison, which took place in Greece (40°36'N, 23°04'E). Comparisons were carried out in daylight and with halogen lamps indoors.

The results from the lamp measurements indicated agreement of the relative spectral responses but alarming discrepancies in absolute values. A discrepancy up to 35 % was detected between two of the participants (GB and GR). The GB team measured about 18 % fainter and GR team 17 % brighter irradiance than specified in the NIST certificate. Moreover, the result by GR was not reproducible with another lamp, but the discrepancy at 320 nm was increased up to 52 % when compared with the GB result that remained at the level of 18 % below the certificate value. The instruments failed to reproduce the relative calibrations produced in the lamp room in solar measurements. The differences of approximately 20 % occurred between the intercomparison in the calibration room
and outdoors. In solar measurements, the ratios of the spectral irradiances compared with the results by the Austrian instrument chosen for the reference varied from 0.9 to 2.1. The necessity of further intercomparisons was indicated by the results obtained.

8.2 The second European intercomparison of spectroradiometers

The first European intercomparison was repeated in 1992 (Gardiner and Kirsch 1993) at the same site as the first one. The instruments participating the first campaign had all undergone modifications for improved performance and four new instruments were included. One of the new instruments was from Germany, one from Netherlands and two were from outside Europe, from Canada and New Zealand.

The results from the second intercomparison were significantly improved when compared with the first comparison. In the laboratory, the agreement of the measured lamp irradiances with the lamp certificates was with one exception within 10%. Results by seven of the instruments agreed better or within 5% with the certificates. In solar measurements, discrepancies from 20% to more than 50% were still observed. A typical feature of the ratios with the reference instrument was a fall-off at shorter wavelengths. Best agreement was found to be between the reference instrument from Austria, Innsbruck, and the GB instrument that remained typically within ±5% down to 310 nm.

8.3 The first Southern Hemisphere intercomparison of spectroradiometers

The first Southern Hemisphere intercomparison (McKenzie et al. 1993) was arranged on one day at Lauder (45°S, 170°E), New Zealand on 23 February 1993. Three spectroradiometers from the National Institute of Water and Atmospheric Research (NIWA) New Zealand, the Fraunhofer Institute (IFU) Germany and the Australian Radiation Laboratory (ARL) Australia took part in the intercomparison. The NIWA and IFU instruments were both cosine corrected and agreement between these instruments was better than ±5%. At noon, (at solar zenith angles less than 42°) all the instruments agreed within ±10%, except at wavelengths shorter than 300 nm. At large solar zenith angles the differences larger than 10% were observed.
8.4 The Nordic intercomparison of UV radiometers

The Nordic intercomparison (NOGIC-93 1994) of UV and ozone instruments was arranged in the autumn 1993 at the observatory of the National Institute of Meteorology at Izaña (28°18'N, 16°29W, 2 367 m.a.s.l.), Tenerife. Altogether 13 UV spectroradiometers, five erythemally weighed broadband UV radiometers and three multiband instruments, participated in the comparison. Besides the Nordic participants from Denmark, Finland, Norway and Sweden, also representatives from Canada, Spain and Greece took part in the intercomparison. The representative from Greece is also a participant of the project of the European Community.

In the dark room, an agreement of the secondary standards, four 1 000 W FEL and one 1 000 W DXW was observed. The calibration of eight spectroradiometers agreed within estimated uncertainties varying from 4.2 to 7.2 %, results of three instruments exceeded the uncertainties by approximately 2 to 4 % and one instrument showed a discrepancy of roughly 60 % (Leszczynski et al. 1994b). In solar radiation measurements, the agreement of all the instruments was found to be within 30 % with a high sun and for wavelengths longer than 300 nm (Josefsson et al. 1994). This was in accordance with the estimated overall uncertainties of the instruments varying from ±8 to ±15 % in solar measurements.
9 CONCLUSIONS

The ground-based measurements are necessary for understanding the factors affecting the transmission of UV through the atmosphere and for evaluating the impact of UV radiation on human health and Earth’s ecosystems. The highest accuracy and precision is required for the measurements carried out for detecting UV trends and for providing data for evaluation of radiative transfer models, whereas for the estimates of health and ecological impacts the requirements are less stringent. The choice for the instrumentation depends on the quality of the problem to be addressed. For the assessment of human health impacts, there should be numerous monitoring sites equipped with relatively simple low-cost instruments, while for physical research a comparatively smaller number but significantly more complicated and expensive instruments are needed.

When comparing the spectral and broadband measurements, the main advantage of the spectral measurements is that the biological effectiveness for any action spectrum can be computed. Moreover, the information on the composition of the atmosphere is given by the fine structure of the spectrum. On the other hand, the disadvantages of the spectroradiometers are the complexity of the instruments together with the laborious calibration and measurement practices requiring trained personnel for operation. The main disadvantage of the broadband meters is that they are limited only to one action spectrum they are designed to follow. However, estimates for various effects following different action spectra may also be obtained by using theoretical correction factors to compensate for the spectral difference between the meter response and desired action spectrum. The advantages of the broadband instruments are that they are easy to operate and can be left unattended, when only the quartz dome is necessary to keep clean.

There are significant sources of error for the solar UV measurements carried out with any type of UV radiometers. The absolute uncertainty of even the highest accuracy spectroradiometric measurements is limited approximately to the level of ±5 to 6 % due to the limited absolute uncertainty of the primary standards. The uncertainty of the solar measurements with commonly used spectroradiometers may easily increase up to more than ±20 %, while comparable or even higher accuracy may be achieved with the broadband radiometers. The uncertainty associated with the measurements with well-characterized and in solar radiation spectroradiometrically calibrated temperature stabilized broadband instruments is estimated to be ±11 %.

To give reliable information on long-term trends or construct a global climatology of terrestrial UV radiation, a UV network should consist only thoroughly
radiometrically characterized instruments operated under standardized calibration and maintenance procedures at all the network sites carried out under strict quality assurance and quality control programmes. To meet both the research and climatological needs, a global UV monitoring network should consist of numerous broadband meters together with a limited number of high precision spectroradiometers.
REFERENCES


APPENDIX A

TECHNICAL SPECIFICATIONS OF THE OL 742 SPECTORADIOMETER OF STUK

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focal length [mm]</td>
<td>100</td>
</tr>
<tr>
<td>Gratings [pcs]</td>
<td>2</td>
</tr>
<tr>
<td>plane/concave</td>
<td>concave</td>
</tr>
<tr>
<td>holographic</td>
<td>yes</td>
</tr>
<tr>
<td>lines/mm</td>
<td>1 200</td>
</tr>
<tr>
<td>Bandwidth (FWHM) [nm]</td>
<td>1.7</td>
</tr>
<tr>
<td>Wavelength step in solar measurements [nm]</td>
<td>1</td>
</tr>
<tr>
<td>Wavelength range [nm]</td>
<td>250...400</td>
</tr>
<tr>
<td>Input optics</td>
<td>teflon diffuser</td>
</tr>
<tr>
<td>Detector</td>
<td>PMT (S-20)</td>
</tr>
<tr>
<td>Weatherproof</td>
<td>no</td>
</tr>
<tr>
<td>Temperature stabilized optics</td>
<td>no</td>
</tr>
<tr>
<td>corrected results</td>
<td>yes</td>
</tr>
<tr>
<td>Dark current removed</td>
<td>yes</td>
</tr>
</tbody>
</table>
APPENDIX B

THE SOLAR UV MEASUREMENT SITES AND NETWORKS


In the following summary on the reported solar UV measurement sites, the information on the U.S. measurements is presented as a separate entity because the U.S. networks as well as measurement equipment have been reported in most detail. The information on other countries has been presented in alphabetical order.

1 THE MEASUREMENT SITES OUTSIDE THE U.S.

The present UV measurement sites and networks are:

<table>
<thead>
<tr>
<th>Country</th>
<th>Site</th>
<th>Measurement equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Australia</td>
<td>network Yallambie Antarctica</td>
<td>BB(^1) (11 pcs) SPR(^2) (4 pcs)</td>
</tr>
<tr>
<td>2 Austria</td>
<td>network Innsbruck Hafelekhar</td>
<td>SPR, BB BB</td>
</tr>
<tr>
<td>3 Belgium</td>
<td>Brussels</td>
<td>SPR</td>
</tr>
<tr>
<td>4 Canada</td>
<td>network Toronto</td>
<td>BB (24 pcs) Brewer</td>
</tr>
<tr>
<td>5 Denmark</td>
<td>Copenhagen Thule Søndre Strømfjord</td>
<td>SPR SPR Brewer</td>
</tr>
</tbody>
</table>

\(^1\) BB: Broadband radiometer  
\(^2\) SPR: Spectroradiometer
<table>
<thead>
<tr>
<th></th>
<th>Country</th>
<th>Location</th>
<th>Instrument Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>Finland</td>
<td>Helsinki, Jokioinen, Tikkakoski, Sodankylä</td>
<td>SPR, BB, Brewer</td>
</tr>
<tr>
<td>7</td>
<td>Germany</td>
<td>Munich, Karlsruhe, Hohenpeissenberg, Potsdam</td>
<td>SPR, Brewer, BB (4 pcs)</td>
</tr>
<tr>
<td>8</td>
<td>Greece</td>
<td>Athens, Crete, Thessaloniki</td>
<td>BB, Brewer</td>
</tr>
<tr>
<td>9</td>
<td>Ireland</td>
<td>Dublin, Galway, Valentia</td>
<td>BB</td>
</tr>
<tr>
<td>10</td>
<td>Italy</td>
<td>Rome, Sicily, Florenze</td>
<td>Brewer</td>
</tr>
<tr>
<td>11</td>
<td>Japan</td>
<td>Not known, Antarctica</td>
<td>SPR, SPR</td>
</tr>
<tr>
<td>12</td>
<td>The Netherlands</td>
<td>de Bilt, Bilthoven</td>
<td>MC(^3), SPR, SPR</td>
</tr>
<tr>
<td>13</td>
<td>New Zealand</td>
<td>Lauder network</td>
<td>BB, SPR, BB (6 pcs)</td>
</tr>
<tr>
<td>14</td>
<td>Norway</td>
<td>Oslo, Ny Ålesund, Tromsø, Trondheim</td>
<td>Brewer, BB, SPR, BB</td>
</tr>
<tr>
<td>15</td>
<td>Portugal</td>
<td>Lissabon, Madeira</td>
<td>Brewer</td>
</tr>
<tr>
<td>16</td>
<td>South Africa</td>
<td>Natal</td>
<td>SPR</td>
</tr>
</tbody>
</table>

\(^3\) MC: Multi-channel instrument
The commonly utilized radiometers in the above listed measurement sites are:

(a) Spectroradiometers like Optronic Models 742 and 752, Spex 1680, EG & G, Bentham and several prototypes yielding typically spectral irradiance from 290 to 400 nm with 1 nm wavelength steps.

(b) Brewer spectroradiometers yielding spectral irradiance from 290 to 325 nm (or to 366 nm) with 0.5 nm wavelength steps.

(c) Broadband radiometers of Robertson-Berger type and prototypes of multi-channel instruments yielding dose rate, irradiance of specific wavelength bands or biologically weighted irradiance.

2 THE SOLAR UV MONITORING SITES OF THE U.S.

In the U.S. several Federal Agencies are conducting UV monitoring and research activities. The existing and planned monitoring networks are presented by Agencies.
2.1 The broadband radiometer network of National Oceanic and Atmospheric Administration

The Robertson-Berger meter network has been operated since 1970 and covers area 30 to 47°N and 75.2 to 122.2°W. The number of the meters has varied and is currently around 15. Not any responsible person or organization was identified. The instruments were not sufficiently characterized prior to deployment and the information needed for estimation of the drift in instrumentation within the period of 11 years is too limited. It has been suggested that the meters represent rather a collection of similar instruments than an integrated network (IARC 1992). The current measurement sites are:

- Albuquerque, New Mexico
- Boulder, Colorado
- Concord, New Hampshire
- El Paso, Texas
- Hilo, Hawaii
- Minneapolis, Minnesota
- S. Burlington, Vermont
- Tucson, Arizona
- Barrow, Alaska
- Chicago, Illinois
- Detroit, Michigan
- Ft. Worth, Texas
- Lihue, Hawaii
- Redwood City, California
- Seattle, Washington

2.2 The spectroradiometer network of the National Science Foundation

The six locations of the spectroradiometric network of the National Science Foundation (NSF) and times when the sites have been established are as follows:

<table>
<thead>
<tr>
<th>Site</th>
<th>Established</th>
</tr>
</thead>
<tbody>
<tr>
<td>1  Antarctica</td>
<td>McMURDO</td>
</tr>
<tr>
<td>2  Argentina</td>
<td>Palmer</td>
</tr>
<tr>
<td>3  Alaska</td>
<td>South Pole</td>
</tr>
<tr>
<td>4  California</td>
<td>Ushuaia</td>
</tr>
<tr>
<td>5  South Pole</td>
<td>Barrow</td>
</tr>
<tr>
<td>6  San Diego</td>
<td></td>
</tr>
</tbody>
</table>

The network instruments are the SUV-100A spectroradiometers manufactured by the Biospherical Instruments Inc. Technical specifications of the SUV-100A spectroradiometers are:
Double grating monochromator (temperature stabilized ±0.5 °C), photomultiplier (cooled to 0 °C), teflon diffuser

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength range</td>
<td>280...500 nm</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>0.75 nm</td>
</tr>
<tr>
<td>Wavelength step</td>
<td>0.1 nm</td>
</tr>
<tr>
<td>Calibration</td>
<td>Automatic: 2 to 4 times a day</td>
</tr>
<tr>
<td></td>
<td>Manual: at 2 to 4 week intervals</td>
</tr>
</tbody>
</table>

2.3 The network of the National Biological Survey

The present network of the national Biological Survey (NBS) consists of eleven sites. Eight of the sites are located in North America and three in Russia, as listed below:

El Malpais, New Mexico  Pereslaval, Russia
Trappeer Creek, Wyoming  Nalchik, Russia
Bear Trap Canyon, Montana Yakutsk, Russia
Little Wood River, Idaho
North King Range, California
Snowy Range, Wyoming
Fairbanks, Alaska
Terry Badlands, Montana

For the network instrument, the UV-B-broadband radiometer made by Yankee Environmental Systems, Inc. has been chosen.

In future, the number of the NBS network instruments is planned to be increased up to 15 by the end of 1995.
2.4 The network of the Smithsonian Institution

The present network of the Smithsonian Institution (SI) consists of multi-channel instruments located in the following sites:

South Pole
Panama
Mauna Loa, Hawaii
Gainesville, Florida
Vicinity of Washington, DC
Point Barrow, Alaska.

The instruments have eight interference filters with nominal 5 nm bandwidths and nominal center wavelengths of 290, 295, 300, 305, 310, 315, 320 and 324 nm. The interference filters are mounted in a rotating filter wheel which positions the filters above a solar-blind photomultiplier (PMT) detector. The wheel rotates at 72 RPM so that spectral data can be obtained at high frequency.

In future, an updated version of the instruments has been designed to be used in the SI network and in other networks, e.g. the USDA network, as well. The new version has 18 interference filters with 2 nm nominal bandwidths covering the range from 290 to 324 at 2 nm spectral resolution. The filter wheel rotates at 15 RPM, so that every wavelength is sampled about once every four seconds. The 8-channel instruments will be replaced as soon as the new model becomes field operational.

2.5 The future network of the Environmental Protection Agency

The Environmental Protection Agency (EPA) is planning to establish 15 monitoring sites equipped with high precision spectroradiometers, and possibly also some broadband measurement sites. Eleven of the spectroradiometers will be located in urban areas that cover 25% of the U.S. population. So far, three of the urban sites have been selected: Atlanta, Georgia, Seattle, Washington, and San Francisco, California. The remaining four sites will be located in background areas.
2.6 The planned network of the U.S. Department of Agriculture

The U.S. Department of Agriculture (USDA) has plans for two networks, one network instrumented with 10 to 14 high resolution spectral radiometers and another network consisting of 30 or more multiband instruments. The wavelength range of the spectroradiometric measurements is planned to be from 290 to 400 nm with 1 nm steps. The multi-channel instruments are planned to have 6 to eight channels within the range of 300 to 360 nm with nominal bandwidths of 2 nm. Since the multi-channel instruments are not yet available, ten sites have been selected to be initially instrumented with broadband instruments. A number of these ten sites are expected to become sites of spectroradiometric measurements as soon as the spectroradiometers will be available. The broadband instruments will be replaced with multi-channel instruments as soon as they will be available. The planned USDA UV monitoring sites are as listed below:

University of California, Colorado State University, University of Georgia
Bledsoe Farm, University of Illinois, Washington State University
Department of Energy Atmospheric, Oklahoma
New Mexico State University, Cornell University, New York
Miami University Oxford, Ohio, University of Maine,
University of Michigan,

1) Site, where the first high resolution spectroradiometer will be installed. (Not site for broadband instrument)

In 1991, the desired specifications of the high resolution spectroradiometers of the USDA network were specified (Gibson 1991) as:

- Wavelength range: 280 to 400 nm
- Dynamic range: from 1 W/(m²·nm) at 400 nm to 10⁻⁶ W/(m²·nm) at 290 nm
- Overall network uncertainty should be less than 10 % (3 sigma) at 295 nm decreasing below 5 % at 340 nm
- Instruments must maintain their calibrations over a 30 °C range for one month
- Bandwidth 1 nm
- Precision ±0.02 nm
- Accuracy ±0.02 nm
- Stray light <10⁻⁶ at 5 bandwidths from the center wavelength
Resolution: 0.001 of the maximum in the scale from 1 to $10^5$ W/m$^2$nm
2·10$^8$ W/m$^2$nm in the range of $\leq 10^6$ W/m$^2$nm

- Precision: minimum 0.2 % of the decade range value
- Accuracy: ±1 % in the range of 1 W/m$^2$nm) to $10^6$ W/(m$^2$nm)

In 1992, it was pointed out that it might be necessary to relax the above listed specifications to achieve reductions in equipment and operational costs (Gibson 1992).
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