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# Instruments to Measure Solar Ultraviolet Radiation

## Part 2: Broadband Instruments Measuring Erythemally Weighted Solar Irradiance

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# 1. INTRODUCTION

This paper is part two of a series of documents dedicated to instruments for the measurement of solar ultraviolet radiation. The series of documents has been drawn up by the WMO Scientific Advisory Group (SAG) on UV Monitoring and the SAG UV Instrumentation Subgroup. The aim of the series is to define instrument specifications and guidelines for instrument characterization that are needed for reliable UV measurements (the reports are available on the WMO GAW publications website).

The spectral instruments described in Part 1 of this series [Seckmeyer et al., 2001] are able to separate the radiation in small wavelength bands with a typical resolution of 1 nm or less. Instruments that give signals that are integrated over a greater wavelength range, e.g. including the whole UVA range, are usually called broadband instruments. There are numerous instruments available that have different spectral responses. Some are designed to measure the integrated UVA (315-400 nm) irradiance, others have a medium bandpass (e.g. 10 nm). In this document we restrict the description to broadband instruments that are designed to determine the erythemally weighted (or "sunburning") irradiance which includes both UVB and UVA radiation. The spectral responsivity of these instruments should therefore resemble the action spectrum for erythema defined by the *Commission International de l'Éclairage* [McKinlay and Diffey, 1987]. The instruments are denoted "Type B-1 instruments" to distinguish them from the spectral instrument types S-1 and S-2 introduced in Part 1 of this series.

The intended audience for this document includes scientists, companies, state organizations and funding agencies dealing with research and monitoring related to measurement of UV irradiance. The information is particularly applicable to agencies providing, disseminating, and using UV Index products. The document should serve as a guide and is based on the current experience and scientific knowledge about the measurement of UV radiation with broadband radiometers.

An advantage of broadband instruments is their low hardware cost compared with spectroradiometers to measure UV irradiance. Broadband instruments tend to have fewer operational problems in the field compared with spectroradiometers because of their simpler design. It should be noted, however, that considerable efforts in quality control and assurance (QA/QC) are required to produce the greatest yield of scientifically useful information. Therefore, maintenance and QA/QC of these instruments introduce substantial additional cost that can far exceed the hardware investment [Webb et al. 1998, 2003, GAW Report No. 126 and 146].

Examinations of broad-band instruments by independent laboratories have revealed that variation of individual instruments from the specifications offered by manufacturers can occur [Leszczynski et al., 1998, 2001; Bais et al., 2001, GAW Report No. 141]. In some instruments of this type, significant temporal changes in the responsivity have been noted [e.g. Weatherhead et al., 1997; Huber et al., 2002b], whereas other instruments of this type have been noted to be quite stable temporally [Lantz et al., 2003]. These changes are difficult to detect without careful examination of the instruments, which requires laboratory equipment specifically designed for this purpose. Therefore, radiometric levels of performance of these instruments may not be assumed but must be verified by careful, periodic characterizations.

Even though broadband instruments have been designed to resemble the CIE erythema action spectrum, the spectral responsivity of broadband instruments often deviates significantly from the ideal erythema action spectrum. Because of the difference between the instruments' spectral response and the erythema action spectrum, correction factors as a function of several atmospheric variables are needed to calculate erythemally-weighted irradiance from these instruments. Recommended procedures for converting the output of the instruments to erythemally-weighted irradiance are given in this document (sections 4.2 and 4.3).

**Figure 1:** View of the broadband radiometers and spectrometers that took part in the COST/LAP/WMO intercomparison in Thessaloniki, Greece, in 1999.

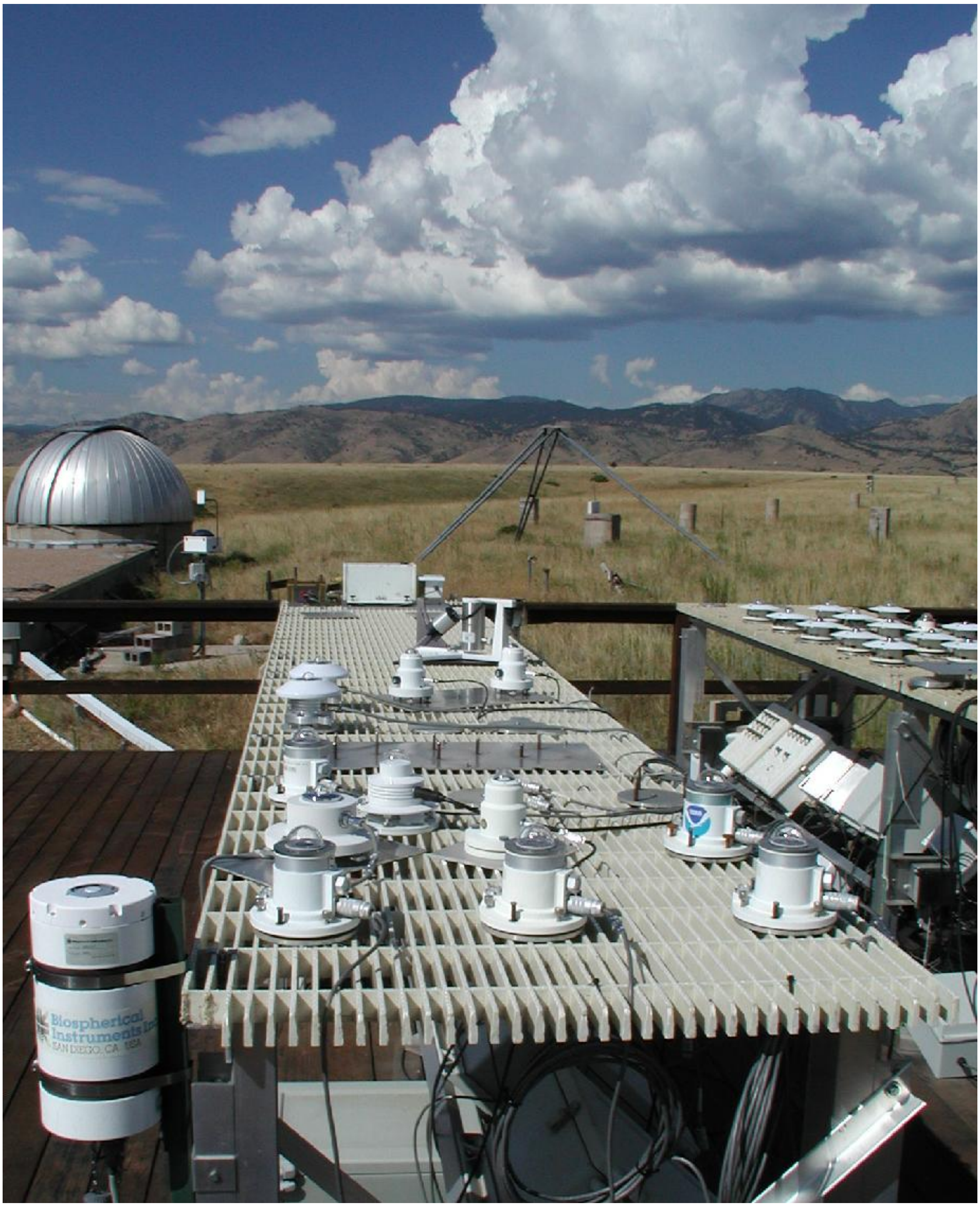

**Figure 2:** **View of 12 UV broadband radiometers at the Central UV Calibration Facility (CUCF), Boulder, CO, USA. These include 4 YES UVB1, 1 older design and 2 newer design EKO, 1 Scintec, 2 Kipp & Zonen, and 1 Solar Light.**

Broadband instruments of this type typically have an associated radiation amplification factor (RAF) of roughly unity, which is comparable to, but not exactly the same as, the RAF of erythemally weighted irradiance. The radiation amplification factor describes the percentage increase in measured UV resulting from a percentage decrease in total ozone [Booth and Madronich, 1994], as described further in the Glossary. In contrast, spectroradiometers are able to measure solar irradiance at wavelengths significantly more sensitive to total ozone changes.

As with all instruments to measure UV irradiance, particular care must be taken with respect to establishing, maintaining and analyzing UV data from broadband instruments. While quality assurance and quality control aspects of all of these issues are still evolving, the recommendations presented in this document are based on current understanding of the requirements. As such, this is a working document and will evolve when new technologies or new objectives for UV radiometry emerge. Readers are therefore encouraged to send comments and suggestions to the lead author (Prof. Dr Gunther Seckmeyer, University of Hannover, email: seckmeyer@muk.uni-hannover.de).

In Section 2 of this document, different objectives for the usage of broadband instruments are compiled. These objectives require certain instrument specifications. In Section 3, specifications for type B-1 instruments are given. Recommendations for the calibration of broadband instruments are finally given in Section 4. A glossary of terms is also provided.

## 2. OBJECTIVES

The desired specifications for broadband instruments to measure erythemally weighted solar radiation are based on the objectives of UV research and the intended use of the data products. These include:

- To provide information on variations of erythemal irradiance (e.g. diurnal or seasonal variability).
- To provide data for public information and awareness (e.g. UV Index).
- To supplement spectral UV measurements (e.g. temporal and spatial interpolation, interpretation of cloud effects).
- To help in quality control of spectral measurements.
- To provide continuous measurements for climatological studies of erythemally weighted irradiance usually within a network and in addition to spectral instruments.
- To help understand geographic differences in erythemally weighted global spectral UV irradiance.
- To contribute to the validation of UV retrievals based on satellite measurements.

Different organizations that are using broadband instruments have defined different objectives for their usage. Two major aims can be distinguished:

a) The first approach is to measure temporal variation in UV at a single site. The data are not corrected to the CIE erythemal response (see chapter 4) because the correction would increase the uncertainty. The uncertainty for this task can be estimated from the standard deviation of several calibrations and by intercomparing the results with a spectroradiometer. This method is not appropriate for intercomparing UV measurements with other instruments.

b) The second approach is the usage of the broadband instruments within a network. The temporal and spatial variations can be assessed by using calibration factors relating each instrument's measurements to absolute irradiances, in this case the irradiance is weighted by the erythemal response.

Broadband instruments are not ideal for trend detection because the expected trends in UV are only a few percent per decade [WMO, 1999, 2003]. While trends of this magnitude may be important to the biosphere, they are difficult to identify at least with broadband sensors currently in use.

For the purpose of climatological studies, the instruments must be properly maintained and an appropriate QA/QC programme has to be applied. Such a climatology is particularly useful for some biological effects and epidemiological studies. The broad spatial distribution of broadband meters around the world can make them useful for establishing climatological information on UV in areas where spectral instruments are not available.

Few of the above objectives can be met without a substantial budget for QA/QC. However, for the purposes of public advisory services regarding current UV levels, less accurate measurements may be appropriate, but it is strongly recommended that the instruments are checked by comparison with model calculations on clear days (when the ozone column and aerosol optical depth are known) or a well calibrated instrument.

## 3. RECOMMENDED SPECIFICATIONS FOR TYPE B-1 INSTRUMENTS

Type B-1 instruments are defined as broadband instruments used for the measurement of erythemally weighted global irradiance. The following instrument specifications are based on the objectives given above, taking into account the limitations of the technology currently available. All quantities introduced in the table are defined in the Glossary. Further remarks on the values are given after the table.

| | **Quantity** | **Quality** |
|---|---|---|
| 1 | Spectral response | a) Radiation amplification factor (RAF) for SZA=30° and 300 DU<br>Desired: 1.21 ± 0.05<br>Recommended: 1.21 ± 0.2<br>Currently in use: 1.21 ± 0.4<br>b) Ratio (CF 75 / CF 30) at 300 DU<br>Desired: 1.0 ± 0.02<br>Recommended: 1.0 ± 0.15<br>Currently in use: 1.0 ± 0.3 |
| 2 | Stability in time (on timescales up to a year) | Currently in use: Better than 5%<br>desired: 2% |
| 3 | Temperature stability | To within ±1°, and temperature preferably recorded |
| 4 | Cosine error | (a) < 10% for incidence angles <60°<br>(b) < 10% to integrated isotropic radiance<br>(c) < 3% azimuthal error at 60° incidence angle |
| 5 | Accuracy of time | Better than ±10s |
| 6 | Response time | < 5 seconds, and preferably < 1 second |
| 7 | Sensitivity to visible and IR solar radiation | < 1%, or below the detection limit |
| 8 | Detection threshold | <0.5 mW m$^{-2}$ (CIE weighted) |
| 9 | Levelling | <0.2 ° |
| 10 | Sampling Frequency | ≤ 1 minute |

For instruments within a network, it is recommended to use those with the least possible variability in their spectral response functions.

The calibration of broad-band instruments is performed by comparing the meter output with the erythemally weighted measurements of a spectroradiometer (see Section 4 for details). The overall calibration uncertainty of a broadband sensor is therefore larger than the uncertainty of the spectroradiometer. The additional uncertainty caused by the transfer of the calibration from the spectroradiometer to the broadband meter should be less than 5%. That means that the minimum overall uncertainty of UV erythemal weighted irradiance measured with meters fulfilling the above criteria is estimated to be 10-15% (two sigma) (Leszczynski et al., 1998; Cede et al., 2002), provided the calibration is based on a well maintained spectroradiometer [Webb et al., 1998].

**Remarks to specifications:**

### A. Spectral response

The importance of mismatches between the instrument response function and the erythemal response function can be specified in terms of:

(1) differences in the instrument-weighted RAF from the erythemally-weighted RAF, and
(2) sensitivity of the Correction Factor (CF) (for converting instrument-weighted UV to erythemally-weighted UV) to changing SZA and ozone amount.

For instruments designed to measure erythemally weighted UV, the RAF should match the RAF for erythema (e.g. RAF= 1.21 at 30 SZA and 300 DU; see Figure 6 for the ozone and SZA dependence of RAF) as closely as possible. The recommended criterion of ±0.2 corresponds to state-of-the-art instruments. Few of the currently available instruments meet the recommended specification. RAF factors as low as 0.8 (instead of 1.2) are found in commonly used instruments.

Ideally the calibration should be independent of SZA and total ozone column. Available instruments do not meet this requirement. Few of the currently available instruments meet the recommended specification. After the application of the correction factors uncertainties in ozone changes and in SZA changes shall lead to additional (to the spectroradiometric calibration) uncertainties in erythemal irradiance of less than 5%. Instruments that meet the “desired” specification are expected to deliver results that need a much smaller post-correction. Ideally, it would be desirable to have instruments that need no post-correction; however this does not seem achievable with current technology.

Calculated values for these criteria are given in Annex 1 and Annex 2 respectively for several instruments (and weighting functions). As can be seen from the Annex 2, failure to correct for dependencies in SZA and ozone leads to errors exceeding 50% for some instruments currently in use. A closer match to the CIE RAF and correction factors independent on SZA and ozone are strongly desired for many scientific applications and manufacturers are encouraged to develop such instruments.

Even small deviations of the instrument’s spectral response from the CIE erythemal action spectrum may lead to significant uncertainties in the measurement of the erythemal irradiance. Deviations within the limits of the RAF desired specification result in differences in the measurements of the erythemal irradiance of about 10-17%, when the mismatch occurs in the UVB, and of about 3-12% if the mismatch occurs in the UVA part of the response function. These differences become larger for high ozone column amounts. Deviations within the limits of the desired specification for the correction factor ratio result in smaller changes of the erythemal irradiance (about 5%), independently of where the spectral mismatch occurs. Further details can be found in Annex 4.

It should be noted here that by applying the appropriate correction factors, these significant differences in the erythemal irradiance are strongly diminished, although the introduced uncertainty cannot be neglected.

### B. Stability in time

The proposed method to determine stability is based on simultaneous measurements with the broadband meter under test and a spectroradiometer. Stability is fulfilled if the ratio S/E remains constant to within ±5% between yearly intercomparisons, where *S* is the signal of the broadband instrument, *E* is the irradiance measured by the spectroradiometer and weighted with the spectral response of the broadband instrument.

Instruments with stabilities better than ±5% are desired for some applications. In particular, the study of long-term atmospheric changes requires instruments that are much more stable than most of those currently in use. Even if some instruments to measure radiation may have a stability of 1-2% per year, the current measurement uncertainties in the UV would not allow an unambiguous determination of such stabilities.

### C. Temperature stability

It is known that many broadband instruments are temperature sensitive. The temperature sensitivity of some types of meters in common use is around 1%/ °C [Dichter et.al., 1994]. Even if temperature coefficients can be derived, temperature stabilization is preferable because the temperature sensed might not be representative of the temperature-dependent element(s) in the instrument. Furthermore the spectral sensitivity of the instrument might change with temperature. In this case corrections due to temperature may not be possible.

### D. Cosine error

Smaller cosine errors would be desirable, but are unrealistic for the majority of the instruments that are currently in use. Definitions of cosine and azimuthal error for cases (a) and (b) are given in the Glossary.

### E. Accuracy in time

Time errors of 10 s can lead to measurable differences as SZA and cloud condition changes. With current technology, uncertainties of less than one second are readily achievable.

### F. Response time

Instruments currently in use have response times that are much smaller than the sampling times normally used.

### G. Sensitivity to visible and infrared solar radiation

This sensitivity should be checked with cut-off filters (e.g. with a Schott Glass GG 400 filter). A description how this may be done can be found in Section 4.1.4.

### H. Detection threshold

The detection threshold may be limited by the digitization resolution of the data logger. A low detection threshold is required to avoid high uncertainties for some applications. For example: a threshold of 2.5 mW $m^{-2}$ corresponds to an UV index of 0.1, which results in an uncertainty of >10% at SZA=70°.

### I. Levelling

Incorrect levelling of the instrument can lead to significant uncertainties. Levelling problems are relatively easy to solve by the use of a simple bubble level (within 0.2°). However, the actual level may not necessarily match the level indicated by this procedure. See the comments on azimuthal error in the Glossary.

### J. Sampling frequency

For some applications 10-minute integrals may be sufficient. For specific research purposes, sampling frequencies of 1Hz may be needed. For example, to comply with Baseline Surface Radiation Network (BSRN) requirements, 1-minute sampling with statistics would be needed.

### Link between specifications and objectives

No instrument available at the time of preparation of this document meets all the desired specifications, therefore this document seeks to provide some guidance in selecting between the currently available instruments according to the user application, see Table 1.

**Table 1. The importance of different specifications in meeting the measurement objectives.**

| | Health advisory | Studies in Polar regions | Ground truth for satellites | Spectroradiometer supplements and QC | Equatorial climatology | Global climatology | Trend Detection [1] | Studies on cloud effects | Radiation monitoring in growth chambers |
|---|---|---|---|---|---|---|---|---|---|
| Spectral response: RAF | ++ | ++ | ++ | | ++ | ++ | ++ | + | ++ |
| Spectral response: CF | + | ++ | ++ | | | ++ | ++ | + | ++ |
| Stability in time | + | ++ | ++ | ++ | ++ | ++ | ++ | | + |
| Temperature stability | + | ++ | ++ | ++ | ++ | + | ++ | | ++ |
| Cosine error | | ++ | + | ++ | | ++ | ++ | ++ | + |
| Accuracy of time | | + | + | ++ | + | + | + | ++ | + |
| Response time | | + | | ++ | | | | ++ | |
| Sensitivity to vis-IR | ++ | ++ | ++ | ++ | ++ | ++ | ++ | ++ | ++ |
| Detection threshold | | ++ | + | + | | + | + | + | + |
| Levelling | | ++ | + | ++ | | + | ++ | ++ | + |
| Sampling frequency | | + | | ++ | | | | ++ | + |

*++ = high priority; + = medium priority; = low priority*

[1] *Broadband instruments are not well suited for trend detection.*

## Remarks on Table 1:

### A. Health advisory

Health advisories (e.g., UV Index reports) often present either the daily maximum or noon-time erythemal levels. Good RAF agreement is needed since ozone values may not be available for same-day corrections needed for public advisories. Low latitudes (<20°) will see little variation in noon time solar elevation, thus instrument performance at low solar elevations will not be critical. If instruments are deployed at high latitudes, where severe ozone depletion may occur, or across a wide range of latitudes, then good performance over a wide range of solar elevations is necessary.

### B. Polar regions

Present unique challenges due to the low solar elevations and extreme temperatures.

### C. Ground truth for satellites

Adherence to RAF is important to avoid using satellite ozone levels to refine the CFs and preserve independence of the sensor's results from the satellites.

### D. Spectroradiometer supplements and QC

Broadband instruments are useful to track short-term changes of the spectroradiometer sensitivity. For this application a close match of instrument and CIE spectral responsivity function is not critical as spectroradiometric measurements can be weighted with the instrument responsivity function. On the other hand, very good time keeping is mandatory for any kind of instrument comparison. The specifications for cosine error, temperature, and levelling have also high priority to keep diurnal variations in the broadband / spectroradiometer ratio small.

### E. Climatology

For climatology applications the comparability of instruments located at different sites is of greatest importance. This stresses the specifications on spectral response, stability, temperature sensitivity and cosine error. At equatorial sites some instrument specifications can be less demanding because measurement uncertainties are usually smaller at high solar elevations.

However, there may be other environmental considerations associated with equatorial regions (see 4.4).

### F. Trend detection

As mentioned above, the instruments discussed in this document are generally not the best suited for trend detection. If instruments are nonetheless used for this purpose, all specifications, and in particular radiometric and spectral stability, have to be met as close as possible.

### G. Studies on cloud effects

These studies require good time keeping and short response times.

### H. Radiation monitoring in growth chambers, greenhouses or phytotrons

Erythemal broadband instruments have been used to monitor UV radiation levels in growth chambers. Great care must be applied when using such instruments for this purpose since plant action spectra generally deviate from the CIE function. In addition, the transmittance of walls of growth chambers is spectrally dependant. Great care is needed when artificial light sources are used, because their spectra differ greatly from the solar spectrum. Correction factors for the SZA and ozone dependence of the calibration factors that are based on unfiltered solar spectra can usually not be applied to measurements performed in such chambers, and special treatment of data may be necessary.

### Ancillary data

- Total ozone column, either measured on-site or from satellite data. The knowledge of total ozone column is necessary for the correction of the measurements to CIE erythemal irradiance (similarly a means of calculating SZA is also required).
- Pyranometer data to enable a further cross checking of instrument's stability in time (Bodeker and McKenzie, 1996).

### Maintenance

1. Daily:

- Check the input optics and clean if necessary.
- Determination of offset (most instruments provide an automated offset-determination during the dark hours, although this should be done manually in Polar Regions). The signals in darkness should be logged.

2. Weekly:

- Checking the humidity indicator and exchange if necessary.
- Checking the effectiveness of temperature stabilization.
- Checking levelling.

3. At least once per year (every six months if possible):

- Checking of instrument stability by comparison to a reference instrument, or spectroradiometer. If these are not available, comparison against a suitable calibrated lamp may be helpful.
- Checking the operation and calibration of electronic supporting devices (data loggers, A/D boards, signal amplifiers, cables, etc.).
- Check the dark stability during the year. Instability may suggest temperature dependence of the electronics or other problems.

4. At deployment, and if quality checks above indicate a problem:

- Verification of the spectral and angular response.
- Check that the instrument is optically levelled.
- Verification of the absolute calibration.

# 4. INSTRUMENT CHARACTERIZATION AND CALIBRATION

For many applications, it is necessary to convert the instrument-weighted signal into CIE-weighted irradiance. It is recognized that in general this conversion depends on the difference between the CIE spectrum and the instrument spectral responsivity, and is therefore a complex function of environmental conditions (solar zenith angle, ozone column, clouds, aerosols etc.). Direct comparisons between the broadband instrument signal and the spectral measurements weighted by the CIE spectrum can provide an estimate of this conversion function [Mayer and Seckmeyer, 1996; Leszczynki et al., 1997; Bodhaine et al., 1998; Bais et al., 2001]. It should be remembered that such empirical functions are valid only for the conditions under which they were derived. Extension to general conditions could be based, for example, on an accurate radiative transfer model for the conditions specific to each measurement (zenith angle, ozone column, etc.). However, the possibility to find the correct input parameters for the radiative transfer models is currently limited especially for cloudy skies. Therefore the conversion function remains uncertain.

## 4.1 Instrument characterizations

As explained in the preceding paragraph, there are differences between the erythema action spectrum and the spectral response of existing broadband radiometers. Therefore, specific knowledge of the spectral response of the UVB radiometer is needed to generate correction factors to obtain erythema-weighted solar irradiance from UVB broadband radiometer measurements. For appropriate quality control and assurance of UVB broadband radiometric data, characterization of the spectral response and cosine response of the radiometer should be completed at regular intervals during a radiometer's field use. To measure the response of the instrument requires well-designed spectral response and cosine measurement systems [Schreder et al., 2004]. It is suggested that independent laboratories carry out spectral response and cosine response characterizations. In addition, the stability and calibration of any instrument needs to be monitored over time.

The following (Sections 4.1.1-4.1.4) gives a general description of typical characterization measurement systems and procedures for stability checks necessary to ensure a quality data product.

### *4.1.1 The spectral response measurement system*

The system used to measure the spectral response of the broadband instrument should include several key components. To begin with the spectral response measuring system requires a spectrally dispersed light source. This can be provided either by a tunable laser or by an optically dispersing instrument such as a monochromator. The following description will concentrate on the latter. Typically, a continuum light source (e.g. xenon arc lamp) that provides sufficient light over the desired wavelength range is imaged onto the entrance slit of a monochromator. The monochromator scans across the desired wavelength range (e.g. 240 – 400 nm) in wavelength increments sufficient to resolve the spectral response. These measurements support the detection of shifts or changes in the spectral response from use in the field, preferably in 1-nm steps or smaller. The stray-light rejection of the monochromator should be sufficient to ensure spectral purity of each measurement step. The light output from the monochromator should be sufficient to give a dynamic range of at least 5 orders of magnitude in the measured spectral response from the device-under-test (DUT). The monochromator should have a band-pass of 2 nm or smaller. The spectral response measurement system should have an optimum balance between acceptable stray-light rejection, band-pass size, wavelength step size and adequate signal throughput to obtain the spectral response curve of the DUT with the desired dynamic range.

The output of the monochromator is collimated and directed to fall onto one of two separate detection systems, the DUT and the reference detector with known spectral response. It is desirable for the output of the monochromator to overfill the detector but in principle this can be difficult to achieve. A measurement of the DUT and the reference detector output signals are taken at each wavelength step. The reference detector measurements are used to normalize the fluctuations in the lamp and to determine the absolute light signal. The signal from the DUT is divided by the signal from the reference detector to produce a ratio that is then normalized to the maximum signal value to produce a normalized spectral sensitivity response function for each radiometer. The wavelength drive of the monochromator should be initially calibrated across the desired wavelength range and checked periodically. The wavelength registration should be performed on a regular basis, i.e. a wavelength accuracy of better than 0.1 nm is desired.

The frequency of characterizing the radiometer for changes in the spectral response depends on whether comparisons with other instruments indicate potential changes in the detector's spectral response, and/or the severity of the conditions at the site (e.g. humidity, cold), but is recommended to occur approximately once per year.

#### *4.1.2 The angular response measurement system*

The angular response measurement system measures the deviation of a broadband radiometer from a perfect Lambertian response. The system is set up to measure from –90° to +90° in increments sufficient to obtain any structure that may be present in the cosine response curve (e.g. 1° increments). Ideally, the system also measures from 0° to 360° in the azimuth to yield a total mapping of the DUT's angular response. The radiometer's cosine response should be measured across at least two specific planes at 90° to each other.

The angular response measurement system should use a radiation source that either resembles a typical solar spectrum or uses monochromatic light at several wavelengths. The collimated light beam should homogeneously overfill the detector window of the DUT. The measurement system should have optically flat black surroundings to limit scattered light. Off-axis light and stray light from a lamp can be minimized by spatially filtering the light beam with baffles.

The following gives a general description of several key components of a cosine measurement system. A detailed description is beyond the scope of this paper. The method described here assumes the DUT is rotated with respect to the light source.

One key component of the measurement system is aligning the collimated light beam perpendicular to the axis of rotation of the rotation stage that holds the DUT. There are several ways to accomplish this. One method would be to use a laser in the position where the light source is located and direct the laser toward the rotation stage. A small mirror can be attached to the instrument mounting plate that is perpendicular to the rotary table, and the 0 degree-position determined by rotating the table until the laser beam is retro-reflected from the mirror back on itself.

A second key component of the cosine measurement system is precisely mounting and aligning the DUT. There are several considerations when mounting the instrument. The DUT should be placed on the mounting plate relative to the light beam that is normal to the rotation axis of the rotation stage in the same manner that it is levelled in the field. Secondly, the DUT is aligned to the light beam allowing a reference point (the measurement starting point) to be established. Also the optical surface of the DUT needs to be placed at the axis of rotation.

A third key component of the cosine measurement system is to have a method of orienting the radiometer in the exact manner in which it is oriented in the field. For example, several networks orient the radiometer in the field with the cable pointed north. For repeating characterizations in the laboratory, the radiometer is oriented in the same fashion for every measurement. In this example, the cosine measurements are taken –90° to 90° in the N-S and E-W directions.

Once these components have been established and the DUT is properly aligned within the measurement system, the DUT is then rotated across the optical beam in the chosen incremental step size, with a measurement of its output taken at each point from –90° to 90°. The first part of this measurement sequence is done with a block in place that just covers the optical entrance of the DUT to measure the diffuse scattered light. In a second step the measurement is repeated without the block. In a third step the radiometer is rotated by 90° in the azimuth and steps 1 and 2 are repeated. Finally the signal from the diffuse radiation is subtracted from the overall signal. This value is then normalized to unity by division with the maximum value. The cosine error can be calculated from these cosine measurements using the definition given in the Glossary.

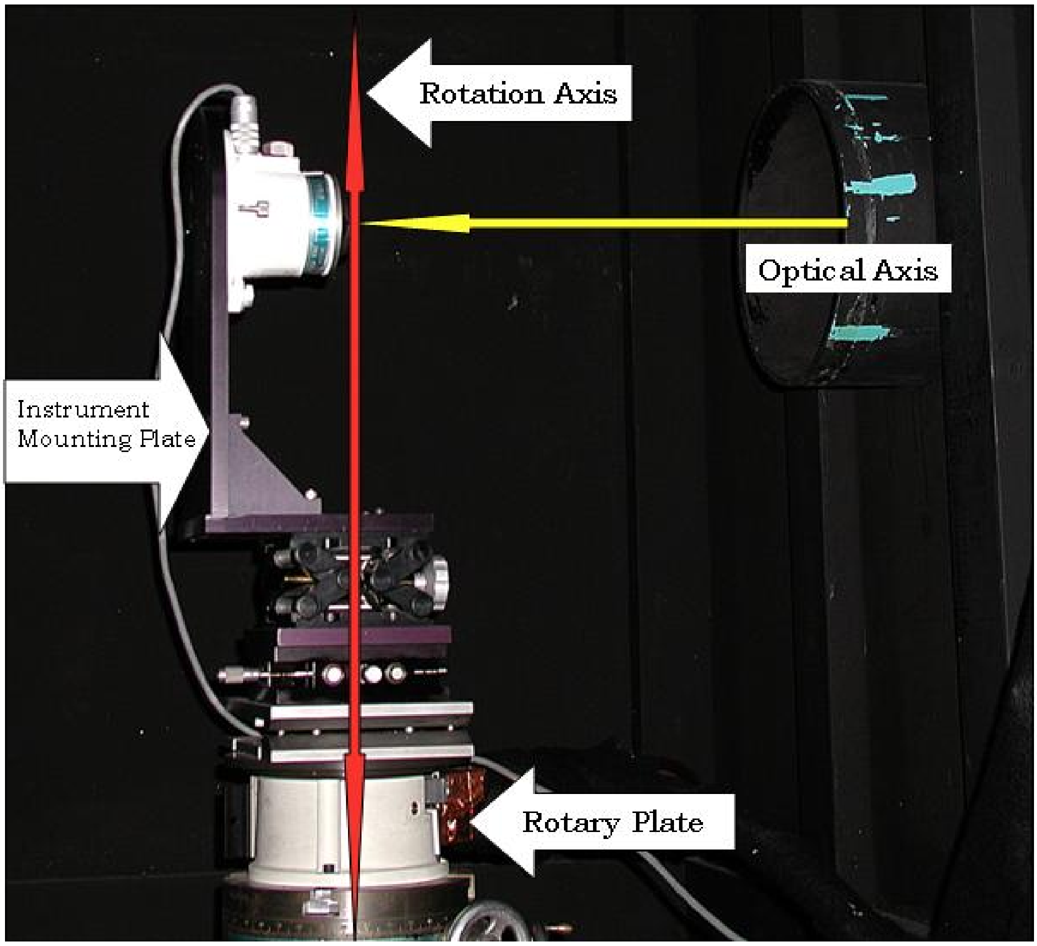

**Figure 3:** **An example of part of a cosine measurement system from the Central UV Calibration Facility (CUCF) at NOAA in Boulder, CO.**

### *4.1.3 Stability tests*

The measurement and the stability criterion should be determined for at least two SZA, one small SZA (e.g. 30°) and one large SZA (e.g. 75°). If no spectroradiometer is available for the stability test it is nonetheless advisable to perform stability tests. In this case a set of broadband instruments must be used. The stability of at least one sensor should be determined by the first method which requires a spectroradiometer. An additional check against a lamp may help to identify changes in the throughput. However, generally, it will be insufficient to check the stability against lamps unless their stability has been verified and their output matches the solar spectrum. The latter is not the case for the widely used tungsten halogen lamps. Changes in relative humidity can also influence instrument response, as discussed in Section 4.4.

### *4.1.4 Visible and infrared leakage test*

The sensitivity to visible and infrared radiation can be tested with cut-off filters that transmit visible and infrared radiation but block UV radiation (e.g. GG 400 produced by Schott). In principle the measurement can be performed outdoors using the sun as the radiation source or in the laboratory, which is the preferred.

*a) laboratory measurement*

Both a solar simulator and a tungsten lamp may be used for this purpose. The measurement must be set up in a way that guarantees that the radiation to be measured passes the filter and that no other radiation irradiates the radiometer (e.g. by the use of baffles). If a tungsten lamp is used no signal should be detected when the cut-off filter is placed between the tungsten lamp and the radiometer. If the combination of the filter and tungsten lamp shows a significant signal, further tests with a solar simulator are recommended due to the high proportion of visible and infrared radiation of the tungsten lamp.

*b) outdoor measurement*

A box should be constructed that blocks all radiation that is not passing the cut-off filter from reaching the radiometer. The temperature inside the box should be measured to guarantee normal operation of the radiation instrument. High or low temperatures inside the box can be avoided by a quick measurement or by forced air flow.

## 4.2 Calibration of broadband instruments

The calibration of a broadband meter usually requires knowledge of the specific spectral sensitivity of that instrument. The spectral responsivity describes the conversion from the detector output (in any units) at each wavelength to monochromatic input (e.g. in W $m^{-2}$ $nm^{-1}$). Measurements of one broadband detector can be directly compared with results of other instruments only if all instruments have exactly the same spectral sensitivity. This is usually not the case even for instruments of the same manufacturer. Therefore, a common reference weighting spectrum is necessary to compare results within a network and globally. Usually the CIE action spectrum for erythema [McKinlay and Diffey, 1987] is used for the interpretation of the results of commonly used broadband meters. A correction is necessary for each instrument, as no instrument has a spectral sensitivity identical to the erythema action spectrum. Therefore the correction depends on the source spectrum for all broadband instruments. The better the agreement between the spectral sensitivity of the detector and the erythema action spectrum, the smaller is the correction, and the less is the sensitivity of the correction to slight variations of the source spectrum (generally the sun). There are several methods in use for calibration of broadband meters, which differ in expenditure and accuracy [Lantz et al., 1999]. In the following, two methods are discussed in detail. The first focuses on best accuracy, the second on valuable accuracy with smaller expenditure. Other methods may give similar results, but their broad usage is restricted due to the necessity for additional special equipment in the laboratory.

### *4.2.1 Suggested calibration method*

The spectral responsivity and the cosine error of the broadband detector have to be known as a requirement for this calibration procedure. This information should either be supplied by the manufacturer or preferably determined in a calibration laboratory. To avoid significant errors, the steeply sloping instrument response should be determined at a spectral resolution (full width at half maximum) of < 2 nm. An appropriate setup might include the use of a Xenon lamp, a double monochromator, and deconvolution techniques to attain the required resolution (details in Section 4.1.1).

The basic step for the calibration is to simultaneously measure the spectral irradiance of the sun with a calibrated spectroradiometer and of the broadband meter, under cloudless sky conditions. The measured spectrum is weighted with the spectral sensitivity of the broadband meter and integrated over all wavelengths relevant for the broadband meter. The result is given in the units [detector-weighted $Wm^{-2}$], relative to a defined wavelength, usually the maximum of the erythema action spectrum at 298 nm or the maximum of the spectral sensitivity of the broadband meter. For different atmospheric conditions such as different solar elevation or ozone column the relation of the detector-weighted spectral integral to the output of the detector after cosine correction should be constant within the uncertainty estimate; otherwise the spectral sensitivity of the broadband meter or the spectroradiometric measurements were incorrect.

Both the spectroradiometric and the broadband measurements have to be corrected for any cosine error (see Seckmeyer et al. 2001, part I of this document). To obtain the correct angular response of the broadband instrument, it is desirable to use a lamp/filter combination, which simulates a typical solar spectrum (details in Section 4.1.2). The conversion of detector-weighted units to erythema-weighted units is done with a radiative transfer model. Such models (e.g. LibRadTran, TUV, STAR, MODTRAN, FASTRT) are now available through the Internet (see Annex

5). The analysis should take into account the actual solar elevation and the actual ozone column, whereas for aerosol amount, altitudes above sea level and typical albedo (mainly snow coverage of the terrain) values are usually sufficient [Bernhard and Seckmeyer, 1999]. Total ozone column is very often available from satellite data. It should be noted that there might be difficulties in using those satellite estimates for special weather conditions due to differences in local ozone column and averaged columns provided by the satellites.

The radiative transfer model is used only for the determination of the relative difference between the two weighting functions (detector sensitivity and erythema action spectrum) and not for comparing absolute irradiances. Therefore, the uncertainty due to the uncertainty of the estimated input parameters is of minor significance. Furthermore, the same model calculations can be used to apply a cosine correction to the reading of the broadband meter, although a complete cosine correction under conditions with varying cloudiness could not be developed so far. Look-up tables or fit functions can be prepared once for each individual detector, which allow fast and routine conversion from the detector reading to erythemally weighted irradiance for many atmospheric conditions.

Summary of suggested calibration method:

- Measure the spectral responsivity and the cosine error of the broadband detector.
- Measure the spectral irradiance of the sun with a calibrated spectroradiometer and simultaneously the signal of the broadband meter, under clear skies.
- Apply cosine corrections to both data sets.
- Weight the measured spectrum with the spectral sensitivity of the broadband meter.
- Determine a scale factor to convert the signal of the broadband meter to detector-weighted irradiance units.
- Use a radiative transfer model to convert from detector-weighted units to erythema-weighted units.

Often the correction of cosine errors is handled differently. A methodology, where the average cosine error is already included in the absolute calibration, is described in Blumthaler (2004). This method adds about 2-3% to the overall uncertainty, but it has the advantage that no further cosine correction of the broadband data has to be applied by the user.

### *4.2.2 Alternative calibration method*

In the alternative calibration method the spectral irradiance is measured with a spectroradiometer simultaneously to a measurement of the signal of the broadband meter. The measured spectral irradiance is weighted with the erythema action spectrum and integrated over all wavelengths relevant for the erythema action. The result is given in the units [erythema-weighted W m$^{-2}$], relative to a defined wavelength (usually the maximum of the erythema action spectrum at 298 nm). The spectroradiometric measurements have to be corrected for any cosine error. The resulting calibration factor relates the spectroradiometrically determined erythemal irradiance with the signal of the broadband meter. Due to the difference between the spectral sensitivity of the detector and the erythema action spectrum this calibration factor is valid only for one specific solar spectrum. To take into account the variations of the solar spectrum (dependence on solar zenith angle, ozone content and to a smaller extent aerosol amount, altitude above see level and albedo), it is necessary to carry out a large number of simultaneous measurements between the spectroradiometer and the broadband meter. From these data the correction factors as a function of solar zenith angle and other atmospheric variables especially total ozone, can be obtained. Also the cosine error of the broadband meter will have different effects depending on the actual ratio of diffuse over global irradiance. An average calibration as a function of solar zenith angle is derived, which will give good results as long as the atmospheric conditions are close to the conditions defined by the average of the calibration measurements. Additionally the dependence on total ozone can be taken into account if a long-term series of simultaneous spectroradiometric measurements is available. This method does not need additional model calculations.

Summary of alternative calibration method:

- Measure the spectral irradiance simultaneously to the broadband meter measurement.
- Deduce the erythemally-weighted spectral irradiance and apply cosine correction.
- Repeat for large number of simultaneous measurements to deduce the correction factor's dependence on SZA and ozone.

A similar method is outlined in Lantz et al. [1999].

### *4.2.3 Comparison to reference instruments*

Within some broadband monitoring networks (e.g. from Austria and Argentina) the stability of the network instruments is routinely checked with a travelling standard detector of the same type. During several days the reference detector is operated side by side with the detector at each station, then it is checked at the central facility (in the laboratory and/or relative to a spectroradiometer) and transported to the next field station. Experience has shown that a level of differences between the field instruments smaller than 5% can be achieved with this method. If significant changes in the diurnal patterns of the ratio of the travelling standard detector to the individual station detector are observed, then it can be assumed that the spectral sensitivity of the field detector has changed and that a recalibration in the laboratory will be necessary.

### *4.2.4 Approximate method*

In some cases, only the measurements at small SZAs (<40°) are important. Here, a single conversion factor rather than a function may be adequate to convert from instrument-weighted irradiance to erythemally-weighted irradiance. This factor, which is a useful parameter for standardization and monitoring the stability of the instrument, should be available for every broadband instrument.

This simplified procedure should be applied only for SZAs <40° to avoid systematic uncertainties (see Annex 2).

## 4.3 Resulting correction functions

The uncertainty budget for the calibration of broadband instruments following the methods above is dominated by the uncertainty of the absolute spectroradiometric measurement and the uncertainty from the cosine error correction algorithm of the broadband meter.

Typical correction factors can be seen in Figures 4a and b, which illustrate the magnitude of the additional uncertainty of the measurements without corrections.

## 4.4 Sensitivity to relative humidity and temperature

In laboratory experiments it has been found that some instruments are sensitive to humidity and - although they are temperature stabilized internally - they are sensitive to environmental temperature [Huber et al. 2002a, 2002b, 2003]. A change of the relative humidity in these instruments from about 17% to 40% (due to poor desiccant) will reduce the spectral sensitivity in the UVA by about 40%, while in the UVB it remains constant to within 3%. This effect has a long time constant (several days) and also some hysteresis. As a consequence the calibration function will show a diurnal variation by a few percent. If the detector is 'dry' due to good desiccant (about 17% relative humidity), then a change of environmental temperature from 20° to 40° (i.e. due to heating by the sun on a clear day) will reduce the spectral sensitivity in the UVA by about 30%, while in the UVB it remains constant to within 3%. However, if the internal relative humidity is high (40%), then the effect of changing temperature is much higher: in this case the spectral sensitivity in the UVB is reduced by about 10%. As a consequence, for a humid detector the changes in temperature over the day can produce absolute changes in the sensitivity of more than 10%. In all cases, a reduction of the temperature (by about 10°) had the inverse effect to the increase of temperature.

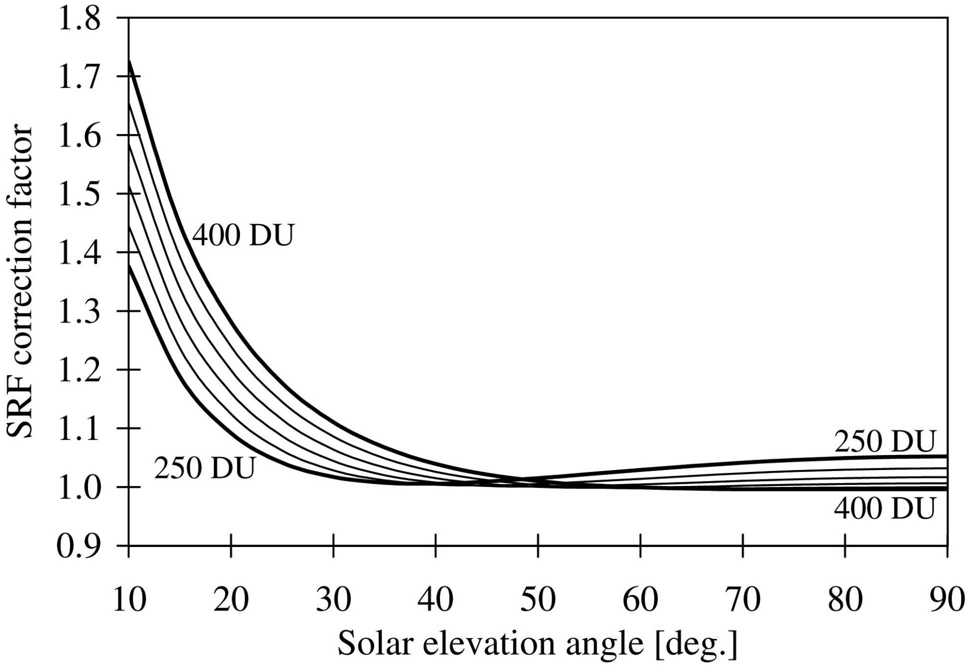

**Figure 4a:** Correction factors for non-ideal spectral responsivity function (SRF) for a typical example of the SL 501 V.3 radiometers, as a function of solar elevation angle for total ozone columns 250 to 400 DU. The correction factors have been normalized to unity at ozone column of 325 DU and solar elevation angle of 50° (from Leszczynski et al., 1995).

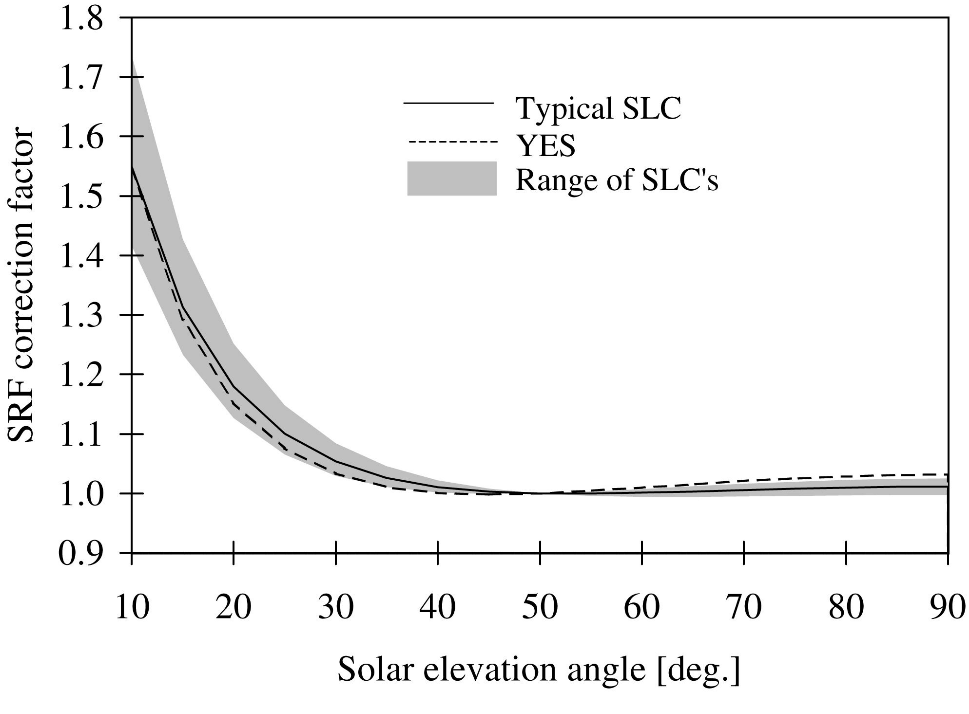

**Figure 4b:** Range of the correction factors for 16 similar instruments (model SL 501 V.3 radiometers). Correction factors for the YES UVB-1 radiometer and the "typical" SLC radiometer have also been included for comparison. The correction factors were calculated for an ozone column of 325 DU and have been normalized to unity at a solar elevation angle of 50° (adapted from Leszczynski et al., 1995).

The absolute calibration of erythemal radiometers therefore changes in the best case (dry detector) by a few percent over the day, with somewhat higher effects at higher SZA (i.e. 2% at 30° SZA, 5% at 70° SZA for 20° change in temperature). This effect can be up to 3 times higher, if the detector is not ideally dry. These results are in good qualitative agreement with the results of field experiments, i.e. during the last LAP/COST/WMO-broadband intercomparison in Greece (Bais et al., 2001). Since the dependencies on temperature and humidity are difficult to characterize and to correct for field experiments they increase the overall uncertainty of the measurement with broadband instruments.

Most characterizations of broad-band meters are made under ideal conditions inside a laboratory. Monitoring generally takes place in less-than-ideal conditions, and laboratory characterizations made at room temperature may not be perfectly applicable to all field conditions encountered. Instrument behaviour in extreme conditions (e.g. hot, humid, or frosty) must be carefully considered. Under these conditions the necessary temperature stabilization may not be achievable. At high solar zenith angle conditions, such as encountered in the winter at mid-latitudes or in polar conditions, pose particular problems because of the imperfect angular and spectral responsivity of the instruments.

Support electronics, in addition to the instrumentation itself, can also pose challenges for some monitoring situations. Low resolution or poor quality of acquisition systems lead to problems for large solar zenith angles. Other stresses on the measurement systems, which can increase the uncertainties in the measurements, include areas that have high humidity or lack adequate power sources. Extremely polluted environments may affect the calibration function.

### 4.5 Instrument intercomparisons

Intercomparisons are useful for directly assessing the intercomparability and accuracy of data from different instruments and/or networks. Based on the results of the previous intercomparisons [Leszczynki et al, 1995; Bais et al., 2001] it is suggested that:

- Intercomparisons are organized every second or third year.
- Observations, including clear skies and small SZA (e.g. SZA < 30), be included if possible.
- At least one spectroradiometer participates.

It is emphasized that instrument intercomparisons are very labour intensive. Results of the intercomparison should be published and available to all interested scientists. Continued efforts at broadband intercomparisons are considered important for understanding the emerging broadband data sets.

Maintenance and transfer of absolute radiometric standards is a difficult and expensive operation. Regional centres should be used - where possible - for instrument characterization and calibration. Presumably these centres will offer the highest possible standards for a wide variety of monitoring efforts in the most efficient manner. Additionally, regional centres will assure a single traceable scale for a region.

## Glossary

**Azimuthal Error**:
The azimuthal error $f_a$ describes the variation of the angular response of a radiometer at a fixed incidence angle $\varepsilon$ as a function of the azimuthal angle $\varphi$. It is defined by

$$f_a(\varepsilon,\varphi) = \left( \frac{Y_{\text{reading}}(\varepsilon,\varphi)}{< Y_{\text{reading}}(\varepsilon) >} - 1 \right) \times 100\%,$$

where

$Y_{\text{reading}}(\varepsilon,\varphi)$ is the reading of the radiometer at angles $\varepsilon$ and $\varphi$

$< Y_{\text{reading}}(\varepsilon) >$ is the average response at incidence angle $\varepsilon$ defined by:

$$< Y_{\text{reading}}(\varepsilon) > = \frac{\sum_{i=1}^{n} Y_{\text{reading}}(\varepsilon,\varphi_i)}{n}.$$

$Y_{\text{reading}}(\varepsilon,\varphi)$ is measured at *n* discrete azimuth angles $\varphi_i$ with 1<=*i*<=*n* at incidence angle $\varepsilon$. The angular response should be measured at least at four different azimuth angles (i.e., 0°, 90°, 180°, and 270°).

**Effect of azimuth error on solar measurements:**
For these calculations it has been assumed that the azimuthal error does not affect the measurement of the diffuse portion of the solar spectrum. It is further assumed that the effect of the azimuthal error is the same as the effect of errors in levelling the instrument. For example, if an instrument with a perfect cosine response is tilted by 1°, this would lead to a ±3% azimuthal error at 60° zenith angle $[\cos(60° - 1°)/\cos(60°) = 1.03]$.

With these assumptions, the ratio *R* defined as

$$\frac{\text{(simulated measurement of an erythemal radiometer with 3\% azimuthal error at 60° zenith angle)}}{\text{(simulated measurement of an erythemal radiometer with perfect angular response)}}$$

becomes:

$$R = [E_S + E_d \times \cos(\Psi - 1°)/\cos(\Psi)] \; / \; [E_S + E_d],$$

where $\Psi$ is solar zenith angle, $E_S$ is diffuse irradiance, and $E_d$ is direct horizontal irradiance. Figure 5 shows ratio *R* for erythemally weighted UV irradiance as a function of $\Psi$ and ozone.

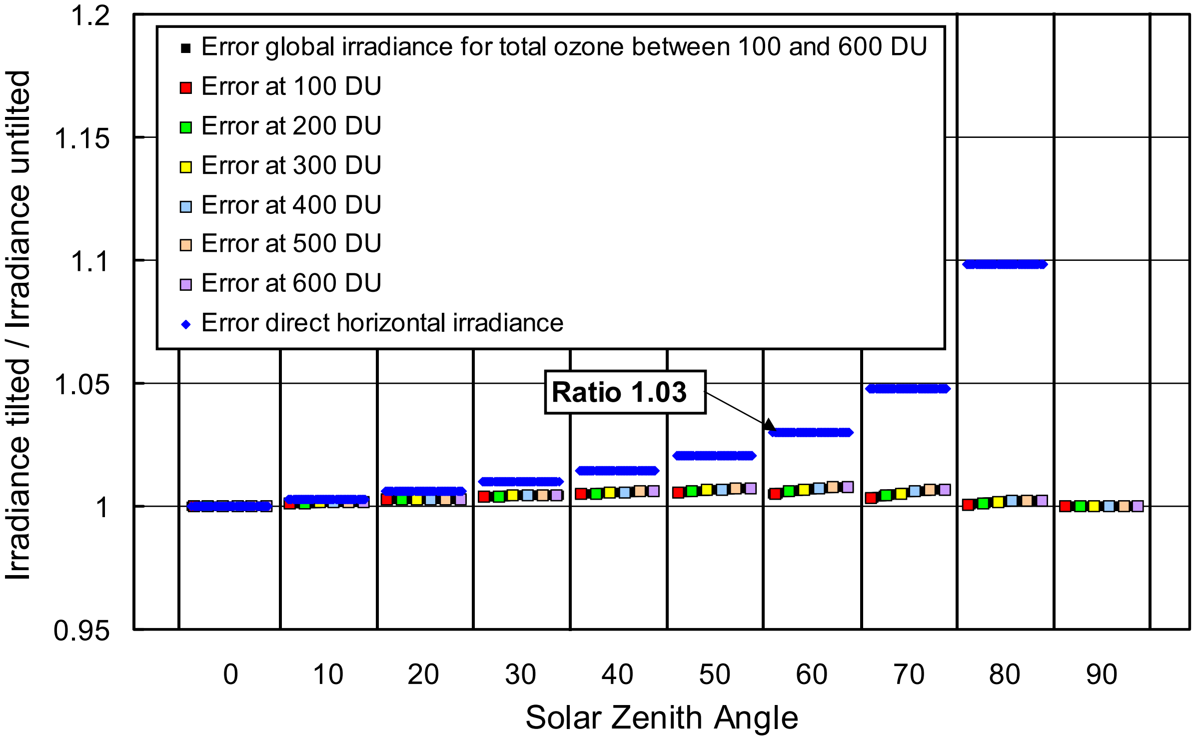

**Figure 5:** **Effect of 3% azimuthal error for $\varepsilon = 60°$ (equivalent to tilting the instrument by 1°) on measurements of erythemally weighted irradiance. The first value in each SZA-bin refers to 100 DU; the last value refers to 600 DU.**

**Biological weighting function or action spectrum:**
Function to describe the wavelength dependence of effects introduced by electromagnetic radiation on biological matter. Depending on the effect and the organism involved, different biological weighting functions $W(\lambda)$ are used. The biologically effective irradiance $E_{\text{weighted}}$ is calculated by multiplying global spectral irradiance $E_G(\lambda)$ with the action spectrum $W(\lambda)$, and integrating over wavelength $\lambda$:

$$E_{\text{weighted}} = \int E_G(\lambda) \times W(\lambda) d\lambda$$

An important weighting function is the action spectrum for erythema proposed by CIE [McKinlay and Diffey, 1987], which describes the wavelength dependence of the reddening of human skin by UV radiation (see also below ‘erythemally weighted irradiance’ $E_{\text{CIE}}$).

**Cosine error:**
The deviation of the angular response of a radiometer from the ideal cosine response is specified with two parameters in this document. The first of these (a) is defined according to [CIE, 1982] and is expressed by the quantity $f_{2a}(\varepsilon,\varphi)$:

$$f_{2a}(\varepsilon,\varphi) = \left( \frac{Y_{\text{reading}}(\varepsilon,\varphi)}{Y_{\text{reading}}(\varepsilon = 0°,\varphi)\ \cos(\varepsilon)} - 1 \right) \times 100\%$$

| | |
|---|---|
| where $\varepsilon$ | is the incidence angle of the radiation, |
| $\varphi$ | is the azimuth angle, |
| $Y_{\text{reading}}(\varepsilon,\varphi)$ | is the reading of the radiometer at angles $\varepsilon$ and $\varphi$, |
| $Y_{\text{reading}}(\varepsilon = 0°,\varphi)\ \cos(\varepsilon)$ | is the ideal response. |

The second specification (b) refers to isotropic radiation and is defined as follows:

$$f_{2b}(\varepsilon,\varphi) = \left( \frac{\int_0^{2\pi} \int_0^{\pi/2} Y_{\mathrm{reading}}(\varepsilon,\varphi) / Y_{\mathrm{reading}}(\varepsilon = 0°,\varphi)\ \sin(\varepsilon)\ d\varepsilon\ d\varphi}{\int_0^{2\pi} \int_0^{\pi/2} \cos(\varepsilon)\ \sin(\varepsilon)\ d\varepsilon\ d\varphi} - 1 \right) \times 100\%$$

If the cosine response of an instrument is wavelength-dependent, cosine errors determined from laboratory studies (e.g., using Xenon or Tungsten lamps) may not be directly transferable to solar irradiance measurements.

**Detection threshold:**
Minimum erythemally weighted irradiance that is detectable. In the scope of this publication, the detection threshold corresponds to a Signal-to-Noise ratio of one.

**Erythemally weighted irradiance $E_{\mathrm{CIE}}$:**
Global spectral irradiance $E_G(\lambda)$ multiplied with the action spectrum for erythema, $C(\lambda)$, proposed by CIE [McKinlay and Diffey, 1987], and integrated over wavelength $\lambda$:

$$E_{CIE} = \int_{250\mathrm{nm}}^{400\mathrm{nm}} E_G(\lambda) \times C(\lambda) d\lambda$$

where $C(\lambda)$ = 1 for $250 < \lambda \le 298$ nm
= $10^{(0.094(298-\lambda))}$ for $298 < \lambda \le 328$ nm
= $10^{(0.015(139-\lambda))}$ for $328 < \lambda \le 400$ nm

**Global spectral irradiance $E_G(\lambda)$:**
Radiant energy *dQ* arriving per time interval *dt,* per wavelength interval *d*$\lambda$, and per area *dA* on a horizontal surface from all parts of the sky above the horizontal, including the disc of the sun itself:

$$E_G(\lambda) = \frac{dQ}{dt dA d\lambda} = E_D(\lambda) \times \cos(\psi) + E_S(\lambda);$$ (units: J $m^{-2}$ $nm^{-1}$ $s^{-1}$ = W $m^{-2}$ $nm^{-1}$ )

where $\psi$ is the solar zenith angle,

$E_D(\lambda)$ is direct normal spectral irradiance, i.e., radiant energy *dQ* arriving from the disk of the sun per time interval *dt*, per wavelength interval *d*$\lambda$, and per area *dA* on a surface normal to the solar beam, and

$E_S(\lambda)$ is diffuse spectral irradiance, i.e., radiant energy *dQ* arriving per time interval *dt,* per wavelength interval *d*$\lambda$, and per area *dA* on a horizontally oriented surface from all parts of the sky above the horizontal, excluding the disc of the sun.

**Radiation Amplification Factor (RAF):**
Radiation Amplification Factors (RAF) are unitless coefficients that describe the relationship between change in total column ozone $O_3$ and change in irradiance *E*. This is often applied to the

erythemally weighted UV irradiance. For small changes in ozone, RAF is defined as the relative fractional change in UV irradiance with fractional change in total column ozone:

$$RAF = -\left(\frac{\Delta E}{E}\right) \Big/ \left(\frac{\Delta O_3}{O_3}\right),$$

where $\Delta E$ and $\Delta O_3$ are the respective changes of $E$ and $O_3$. For the erythema action spectrum, RAF is approximately 1.1 [Madronich et al., 1991]. This means that a 1% decrease in total column ozone will cause a 1.1% increase in erythemally weighted irradiance, assuming that all parameters except ozone are constant. Note that this linear relationship can only be applied with sufficiently small uncertainties if changes in total column ozone are small. For larger changes in ozone, a power formulation of the RAF as suggested by Booth and Madronich [1994] has to be used:

$$RAF = \frac{\ln(E^*_{\mathrm{CIE}} / E_{\mathrm{CIE}})}{\ln(O_3 / O_3^*)}$$

where $E^*_{\mathrm{CIE}}$ is erythemally weighted irradiance corresponding to ozone column $O_3^*$, and $E_{\mathrm{CIE}}$ is erythemally weighted irradiance corresponding to ozone column $O_3$. Further analysis shows that RAF coefficients are not constant but depend on solar zenith angle (SZA) and ozone column. Figure 6 illustrates this dependency. The figure was constructed from model spectra that were calculated for different solar zenith angles and total column ozone. The spectra were then weighted with the CIE action spectrum for erythema, and the corresponding RAF coefficients were calculated using the power definition given above. RAF coefficients tend to be highest at small SZA and 300 DU, and lowest at large SZA and high ozone concentrations. For example, for SZA=20° and 300 DU the erythemal RAF is 1.22; for SZA= 70° and 600 DU it is 0.70.

The sensitivity of measurements from type B-1 instruments to changes of total column ozone should ideally match the dependence of erythemal irradiance and column ozone described by the RAF coefficients.

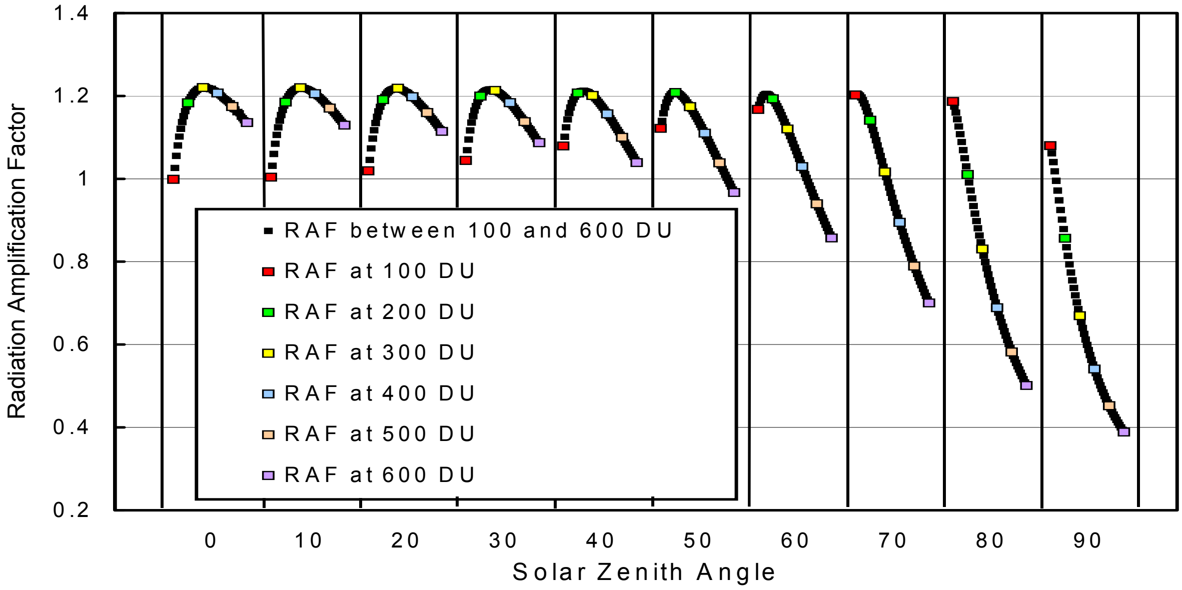

**Figure 6:** **Radiation amplification factor for erythemally weighted irradiance as a function of SZA, for several total column ozone amounts. RAF values were calculated in SZA-steps of 10° and steps of 10 DU in ozone column. The first value in each SZA-bin refers to 100 DU; the last value refers to 600 DU.**

**Total ozone column:**
Height of a hypothetical layer which would result if all ozone molecules in a vertical column above the Earth's surface were brought to standard pressure (1013.25 hPa) and temperature (273.15 K). The total ozone column is usually reported in milli-atmosphere-centimeters (m-atm-cm), commonly called 'Dobson units' (DU).

One DU

- Defines the amount of ozone in a vertical column which, when reduced to standard pressure and temperature, will occupy a depth of 0.01 mm.
- Corresponds to $2.69 \cdot 10^{16}$ molecules/cm$^2$.

**UV index:**
A measure of the intensity of solar UV radiation at the Earth's surface, which is used for public information. In [WMO, 1994] it is stated:

1. Calculation of the erythemally weighted irradiance $E_{\mathrm{CIE}}$ (see above) by utilization of the CIE action spectrum [McKinlay and Diffey, 1987] normalized to 1.0 at 298 nm.
2. A minimum requirement is to report irradiance values at local solar noon.
3. The index is expressed by multiplying the weighted irradiance in W/m$^2$ by 40.0 (this will lead to an open-ended index which is normally between 0 and 16 at sea level, but with larger values possible at high altitudes).

A modified definition of the UV index is given in [ICNIRP, 1995]. The definitions of the UV index given above may be revised in the future.

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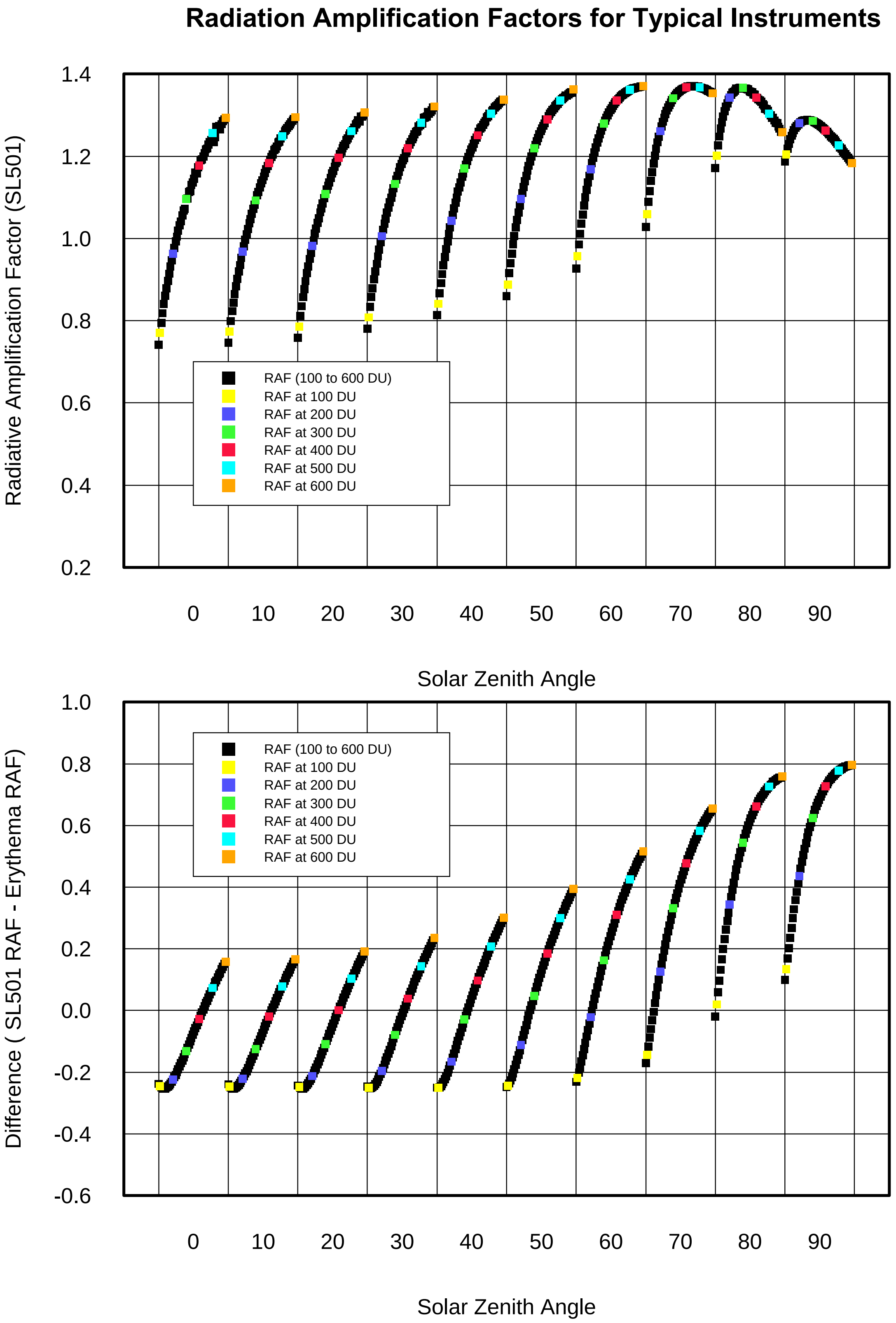

**Figure 7:** **RAFs as a function of ozone and solar zenith angle calculated for a typical Solar Light 501 radiometer (top) and difference to RAF for erythema.**

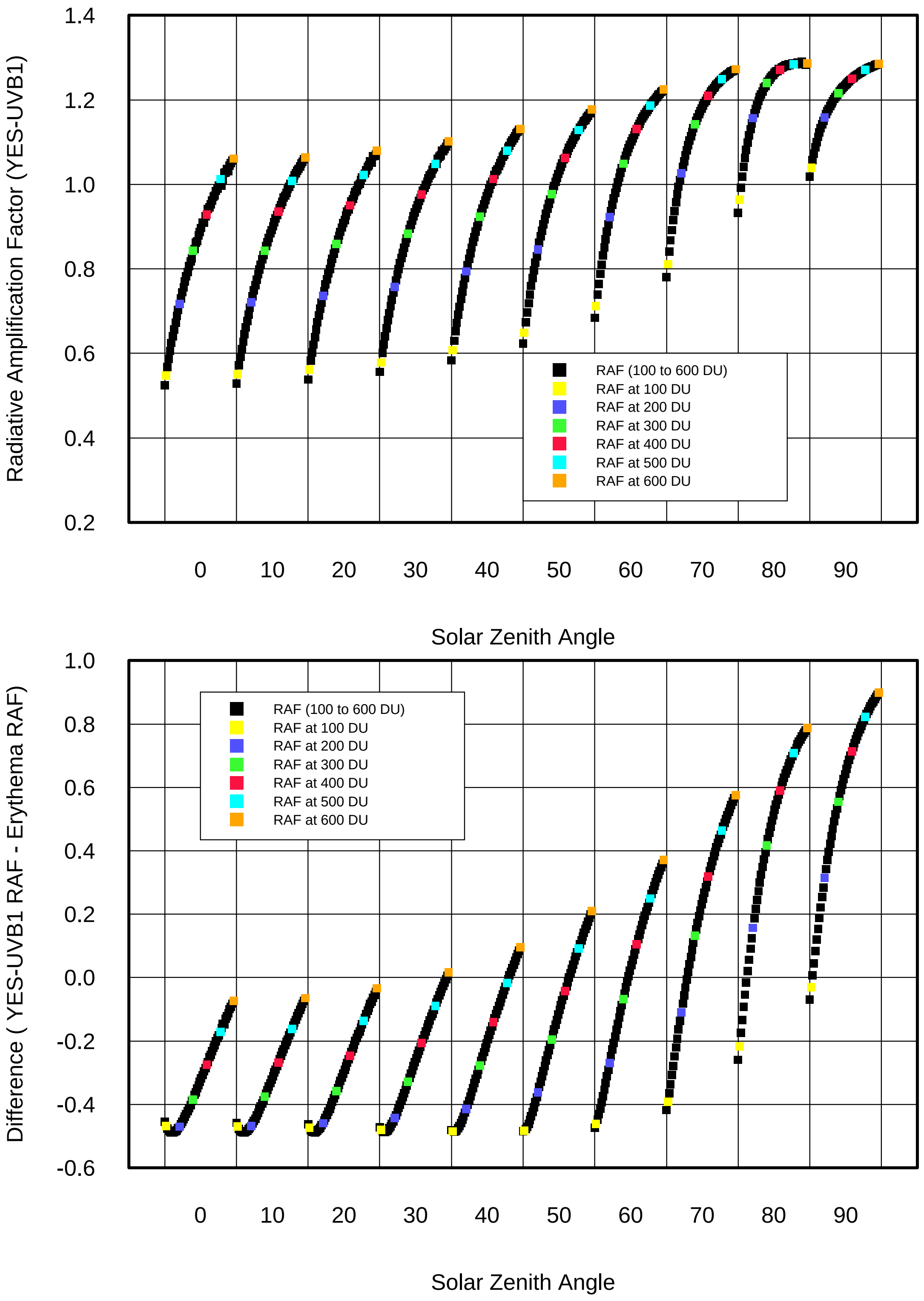

**Figure 8:** **RAFs as a function of ozone and solar zenith angle calculated for a typical YES UVB1 radiometer (top) and difference to RAF for erythema.**

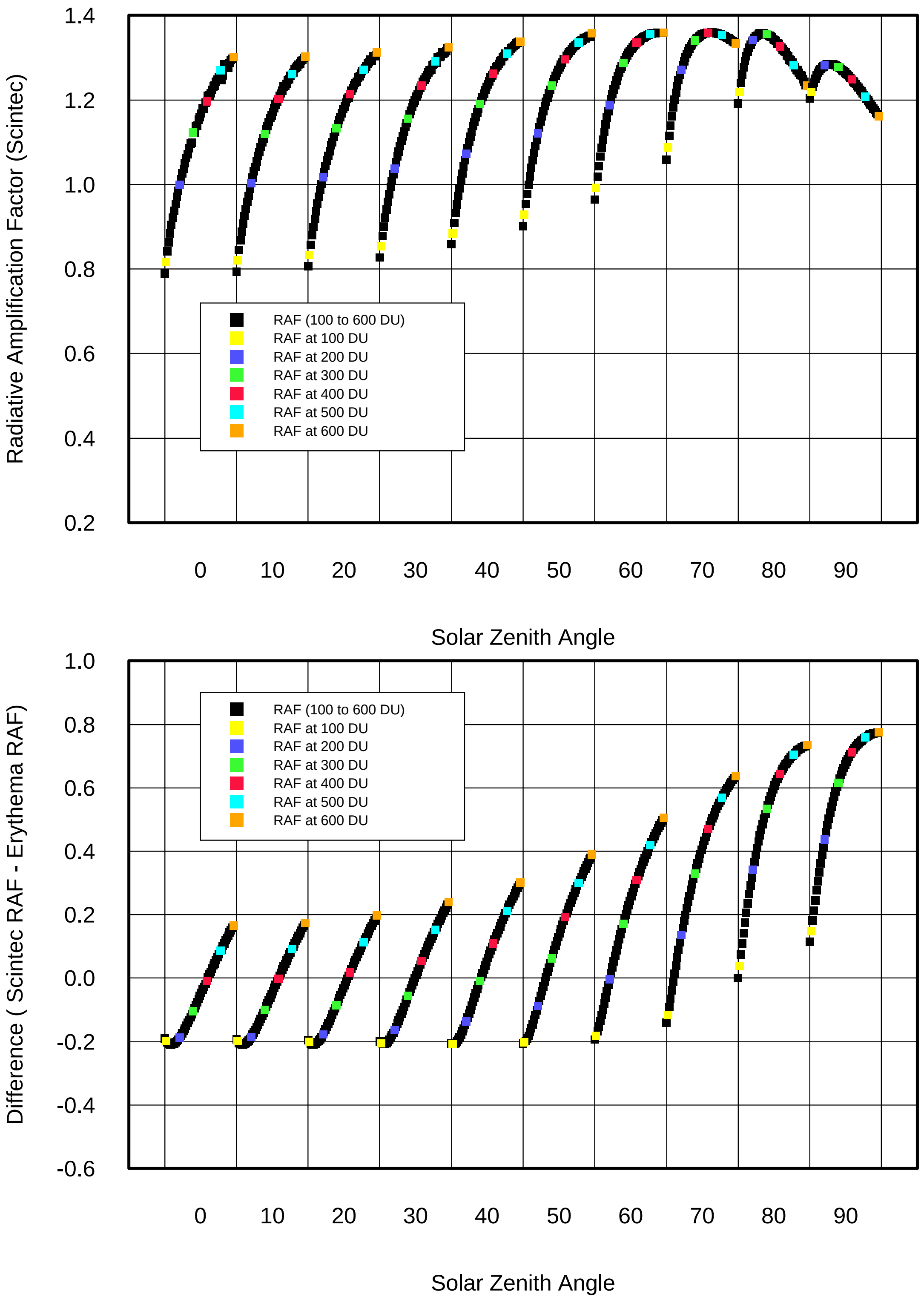

**Figure 9:** **RAFs as a function of ozone and solar zenith angle calculated for a typical Scintec radiometer (top) and difference to RAF for erythema.**

**Table 1:** **RAFs for a wider range of instruments (and weighting functions) for SZA=30, Ozone= 300 DU. Under these conditions, the RAF for erythema is 1.2. The number of instruments contained in the following table is those that had been tested by the authors in 1999. They do not reflect the abundance of instruments in operation.**

| Instrument Type | Quantity | RAF 30°-300 DU<br>Average | Max | Min |
|---|---|---|---|---|
| YES_UVB1 | 51 | 0.861 | 1.004 | 0.799 |
| Solar_Light_501 | 33 | 1.116 | 1.184 | 0.939 |
| SCINTEC/K&Z | 3 | 0.924 | 0.986 | 0.888 |
| VITAL | 1 | 1.157 | 1.157 | 1.157 |
| International_Light | 1 | 1.130 | 1.130 | 1.130 |
| RB_Meter (old) | 1 | 0.702 | 0.702 | 0.702 |
| K&Z_CUV* | 1 | 0.029 | 0.029 | 0.029 |
| EKO* | 1 | 0.711 | 0.711 | 0.711 |
| UVB (280-315nm)** | 1 | 0.932 | 0.932 | 0.932 |
| UVA (315-400nm)** | 1 | 0.020 | 0.020 | 0.020 |

*The instruments marked by * are not intended to have an erythemal response function and therefore cannot be expected to have a RAF of about 1.*

*** The UVB and UVA are calculated values only and do not refer to existing instruments*

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## Correction Factors to Convert Instrument Weighted Irradiances to Erythemally-Weighted Irradiances for some Available Instruments

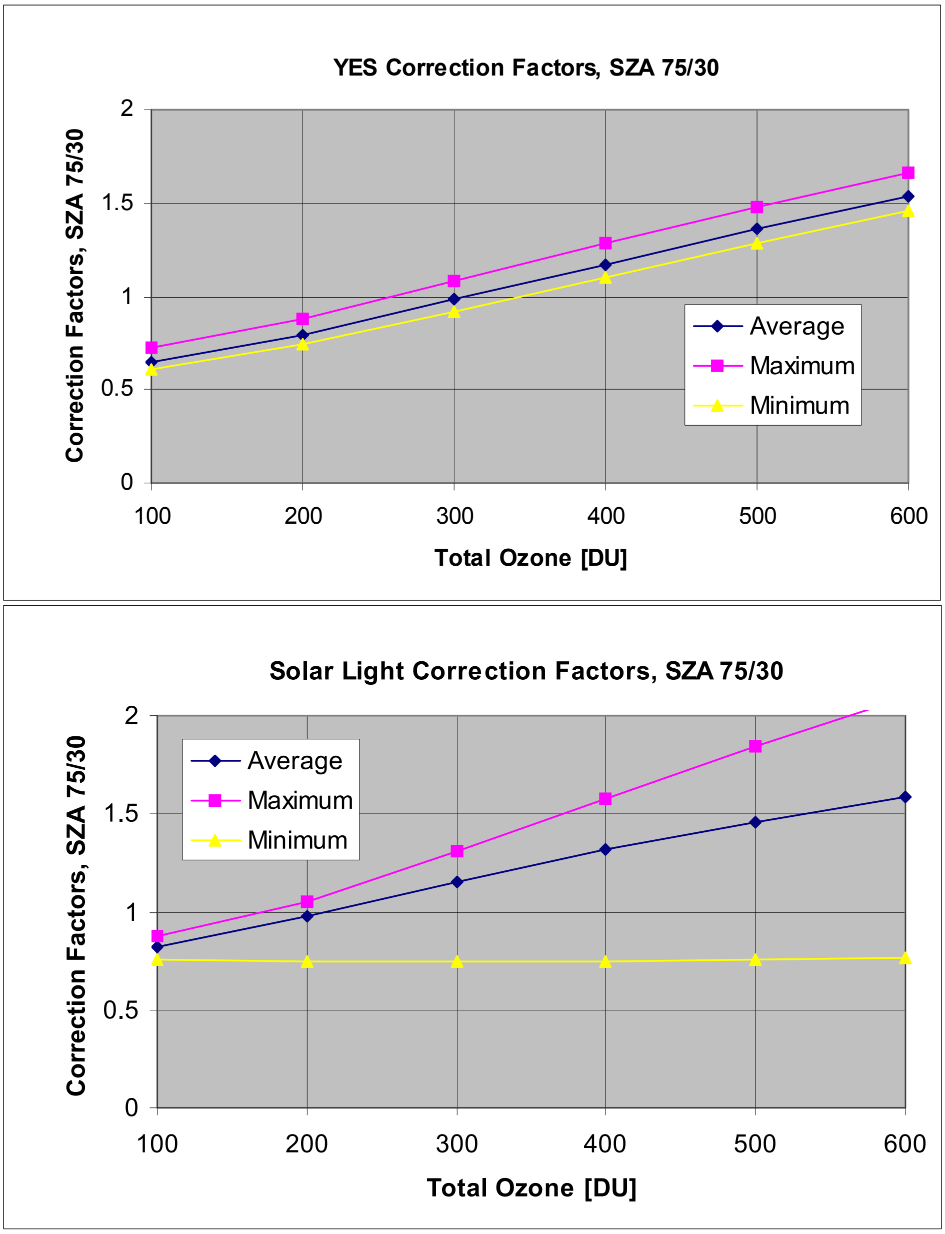

Figure 10: Correction Factors to convert instrument-weighted irradiances to erythemally-weighted irradiances for examples of commonly used instruments, as determined from measurements undertaken at CUCF. Graphs show examples of the ratio of correction factors as functions of ozone amount for two specified SZA (30, 75).

**Table 2: Statistics of the Correction Factors and their ratio at 75° and 30° SZA derived from the spectral response functions of a number of different broadband radiometers as they were supplied by their manufacturers in year 2000. The last two columns show the number of these instruments for which the CF ratio is within 10% or 20% of its ideal value.**

| | | | CF 75°SZA | | | CF 30°SZA | | | CF Ratio 75°/30° | | | Quantity | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **TOC** | **Instrument type** | **Quantity** | **Average** | **Max** | **Min** | **Average** | **Max** | **Min** | **Average** | **Max** | **Min** | **±10%** | **±20%** |
| **300 D.U.** | YES_UVB1 | 51 | 0.174 | 0.323 | 0.129 | 0.188 | 0.304 | 0.150 | **0.918** | 1.063 | 0.860 | 32 | 51 |
| | Solar_Light_501 | 33 | 0.592 | 0.781 | 0.407 | 0.513 | 0.659 | 0.383 | **1.153** | 1.308 | 0.746 | 7 | 22 |
| | SCINTEC/K&Z | 3 | 0.311 | 0.349 | 0.285 | 0.343 | 0.369 | 0.325 | **0.912** | 1.074 | 0.813 | 1 | 3 |
| | VITAL | 1 | 0.637 | 0.637 | 0.637 | 0.647 | 0.647 | 0.647 | **0.985** | 0.985 | 0.985 | 1 | 1 |
| | International_Light | 1 | 2.925 | 2.925 | 2.925 | 3.242 | 3.242 | 3.242 | **0.902** | 0.902 | 0.902 | 1 | 1 |
| | RB_Meter (old) | 1 | 0.086 | 0.086 | 0.086 | 0.120 | 0.120 | 0.120 | **0.717** | 0.717 | 0.717 | 0 | 0 |
| | K&Z_CUV* | 1 | 0.002 | 0.002 | 0.002 | 0.006 | 0.006 | 0.006 | **0.333** | 0.333 | 0.333 | 0 | 0 |
| | EKO* | 1 | 0.150 | 0.150 | 0.150 | 0.221 | 0.221 | 0.221 | **0.679** | 0.679 | 0.679 | 0 | 0 |
| | UVB (280-315nm)** | 1 | 0.167 | 0.167 | 0.167 | 0.128 | 0.128 | 0.128 | **1.305** | 1.305 | 1.305 | 0 | 0 |
| | UVA (315-400nm)** | 1 | 0.001 | 0.001 | 0.001 | 0.004 | 0.004 | 0.004 | **0.250** | 0.250 | 0.250 | 0 | 0 |
| **400 D.U.** | YES_UVB1 | 51 | 0.189 | 0.363 | 0.138 | 0.173 | 0.173 | 0.136 | **1.087** | 1.247 | 1.015 | 36 | 50 |
| | Solar_Light_501 | 33 | 0.668 | 0.887 | 0.449 | 0.507 | 0.507 | 0.370 | **1.318** | 1.549 | 0.750 | 0 | 2 |
| | SCINTEC/K&Z | 3 | 0.322 | 0.390 | 0.284 | 0.322 | 0.322 | 0.312 | **1.004** | 1.246 | 0.856 | 1 | 2 |
| | VITAL | 1 | 0.624 | 0.624 | 0.624 | 0.642 | 0.642 | 0.642 | **0.972** | 0.972 | 0.972 | 1 | 1 |
| | International_Light | 1 | 2.779 | 2.779 | 2.779 | 3.174 | 3.174 | 3.174 | **0.876** | 0.876 | 0.876 | 0 | 1 |
| | RB_Meter (old) | 1 | 0.084 | 0.084 | 0.084 | 0.104 | 0.104 | 0.104 | **0.808** | 0.808 | 0.808 | 0 | 1 |
| | K&Z_CUV* | 1 | 0.002 | 0.002 | 0.002 | 0.005 | 0.005 | 0.005 | **0.400** | 0.400 | 0.400 | 0 | 0 |
| | EKO* | 1 | 0.143 | 0.143 | 0.143 | 0.193 | 0.193 | 0.193 | **0.741** | 0.741 | 0.741 | 0 | 0 |
| | UVB (280-315nm)** | 1 | 0.232 | 0.232 | 0.232 | 0.122 | 0.122 | 0.122 | **1.902** | 1.902 | 1.902 | 0 | 0 |
| | UVA (315-400nm)** | 1 | 0.001 | 0.001 | 0.001 | 0.003 | 0.003 | 0.003 | **0.333** | 0.333 | 0.333 | 0 | 0 |

*The instruments marked by * are not intended to have an erythemal response function and therefore cannot be expected to have a CF ratio of 1.*

*** The UVB and UVA are calculated values only and do not refer to existing instruments*

## Solar Spectral Irradiance Used to Derive and Check the Specification of this Document

Global irradiance spectra used for the calculation of Radiation Amplification Factors and Correction Factors were generated with the radiative transfer model UVSPEC/libRadtran, Version 0.99 beta, available at www.libradtran.org. Apart from SZA and total column ozone the following model parameters were used:

| Parameter | Value |
|---|---|
| Extraterrestrial Spectrum | SUSIM/ATLAS3 for wavelengths smaller than 408 nm |
| Atmospheric constituents and temperature profiles | Air Force Geophysics Laboratory mid-latitude summer |
| Ozone absorption cross section | Bass and Paur |
| Radiative Transfer Solver | Pseudospherical Disort |
| Number of streams | 12 |
| Albedo | 0.03 |
| Air pressure | 1013 hPa |
| Aerosol parameterization | With Angstroem turbidity formula: $\tau(\lambda) = \beta \lambda^{-\alpha}$ ; and setting $\alpha$=1.3 and $\beta$=0.05 |
| Aerosol single scattering albedo | 0.99 |
| Altitude above sea level | 0 km |

Spectra were calculated in high resolution and then convolved with a triangular function of 1 nm full width at half maximum. The spectra are now available in wavelength steps of 0.5 nm, for solar zenith angles (SZA) between 0° and 90° in steps of 10°, and for ozone values between 90 and 610 DU in steps of 10 DU. A subset of these spectra for SZA = 30° and 75°, and ozone values of 300 and 400 DU are given below in wavelength steps of 1 nm.

From these spectra, Radiation Amplification Factors were calculated in dependence of SZA and total column ozone with the following formula:

$$RAF(s,o) = \frac{\ln[E(s,o-20)/E(s,o+20)]}{\ln[(o+20/o-20)]},$$

where $s$ = SZA and $o$ = total column ozone in Dobson Units.

For example:

$$RAF(SZA=30, ozone=300DU) = \frac{\ln[E(30,280)/E(30,320)]}{\ln[(320/280)]}$$

## Global spectral irradiance at SZA = 30°, 75°, and total column ozone = 300, 400 DU

| Wavelength [nm] | SZA=30 Ozone=300 [mW(m$^{-2}$ nm$^{-1}$)] | SZA=30 Ozone=400 [mW(m$^{-2}$ nm$^{-1}$)] | SZA=75 Ozone=300 [mW(m$^{-2}$ nm$^{-1}$)] | SZA=75 Ozone=400 [mW(m$^{-2}$ nm$^{-1}$)] |
|---|---|---|---|---|
| 285.0 | 2.9556e-08 | 3.3343e-11 | 3.7569e-11 | 6.3623e-14 |
| 286.0 | 2.8993e-07 | 5.0808e-10 | 3.3784e-10 | 8.5445e-13 |
| 287.0 | 2.3697e-06 | 7.7817e-09 | 2.4855e-09 | 1.0896e-11 |
| 288.0 | 1.8757e-05 | 1.2424e-07 | 1.7778e-08 | 1.4539e-10 |
| 289.0 | 0.00014259 | 1.5798e-06 | 1.2797e-07 | 1.6436e-09 |
| 290.0 | 0.00076146 | 1.2638e-05 | 6.6234e-07 | 1.211e-08 |
| 291.0 | 0.0032719 | 8.9914e-05 | 2.8014e-06 | 7.9339e-08 |
| 292.0 | 0.011667 | 0.00047469 | 1.0063e-05 | 4.0107e-07 |
| 293.0 | 0.037438 | 0.0022597 | 3.3265e-05 | 1.8648e-06 |
| 294.0 | 0.10083 | 0.0082594 | 9.3781e-05 | 6.8397e-06 |
| 295.0 | 0.2768 | 0.031723 | 0.00027906 | 2.7135e-05 |
| 296.0 | 0.69137 | 0.10211 | 0.00076171 | 9.1576e-05 |
| 297.0 | 1.2647 | 0.2409 | 0.0015815 | 0.00023412 |
| 298.0 | 2.5028 | 0.57128 | 0.0035289 | 0.00059978 |
| 299.0 | 4.4713 | 1.2357 | 0.0075354 | 0.0014636 |
| 300.0 | 6.3667 | 2.0468 | 0.012975 | 0.0027474 |
| 301.0 | 11.648 | 4.4043 | 0.031765 | 0.0072191 |
| 302.0 | 15.689 | 6.6385 | 0.055694 | 0.013176 |
| 303.0 | 32.441 | 15.475 | 0.16378 | 0.040644 |
| 304.0 | 39.166 | 20.035 | 0.25095 | 0.06485 |
| 305.0 | 55.911 | 31.63 | 0.53525 | 0.15163 |
| 306.0 | 60.326 | 36.245 | 0.7419 | 0.22507 |
| 307.0 | 83.969 | 54.329 | 1.4718 | 0.50682 |
| 308.0 | 104.4 | 71.02 | 2.3149 | 0.86659 |
| 309.0 | 104.78 | 74.342 | 2.8918 | 1.1909 |
| 310.0 | 116.67 | 87.578 | 4.2961 | 1.9948 |
| 311.0 | 183.05 | 140.76 | 7.647 | 3.7551 |
| 312.0 | 181.82 | 145.34 | 9.4326 | 5.1393 |
| 313.0 | 207.67 | 170.74 | 12.5 | 7.2662 |
| 314.0 | 227.82 | 191.22 | 15.467 | 9.5608 |
| 315.0 | 238.1 | 205.47 | 18.801 | 12.441 |
| 316.0 | 212.6 | 186.12 | 18.256 | 12.612 |
| 317.0 | 301.88 | 268.59 | 28.327 | 20.341 |
| 318.0 | 281.99 | 254.57 | 28.862 | 21.688 |
| 319.0 | 312.12 | 288.95 | 36.888 | 29.662 |
| 320.0 | 345.9 | 317.72 | 39.049 | 30.732 |
| 321.0 | 353.85 | 334.74 | 47.444 | 40.555 |
| 322.0 | 343.43 | 321.66 | 43.39 | 36.027 |
| 323.0 | 321.89 | 306.37 | 44.779 | 38.979 |
| 324.0 | 394.58 | 382.26 | 60.792 | 55.498 |
| 325.0 | 413.87 | 396.68 | 59.889 | 53.023 |
| 326.0 | 524.79 | 510.14 | 82.656 | 76.276 |
| 327.0 | 536.43 | 524.86 | 87.738 | 82.375 |
| 328.0 | 502.1 | 487.33 | 78.411 | 71.981 |
| 329.0 | 563.4 | 555.15 | 96.306 | 92.338 |
| 330.0 | 617.84 | 609.95 | 106.81 | 102.92 |
| 331.0 | 543.94 | 532.77 | 89.833 | 84.576 |
| 332.0 | 562.84 | 557.13 | 99.077 | 96.206 |
| 333.0 | 551.01 | 546.24 | 97.939 | 95.495 |
| 334.0 | 550.92 | 544.72 | 96.519 | 93.374 |
| 335.0 | 585.95 | 582.96 | 106.64 | 105.07 |
| 336.0 | 507.37 | 505.28 | 92.977 | 91.864 |
| 337.0 | 490.02 | 486.38 | 88.157 | 86.244 |
| 338.0 | 545.03 | 542.14 | 99.443 | 97.912 |
| 339.0 | 582.95 | 581.67 | 108.49 | 107.8 |
| 340.0 | 637.18 | 636.81 | 119.83 | 119.64 |
| 341.0 | 579.4 | 579.41 | 109.46 | 109.47 |
| 342.0 | 608.86 | 608.86 | 115.19 | 115.19 |
| 343.0 | 640.62 | 640.62 | 121.37 | 121.37 |
| 344.0 | 509.81 | 509.81 | 96.719 | 96.719 |
| 345.0 | 580.56 | 580.56 | 110.32 | 110.32 |
| 346.0 | 577.14 | 577.14 | 109.82 | 109.82 |
| 347.0 | 606.87 | 606.87 | 115.64 | 115.64 |

| | | | | |
|---|---|---|---|---|
| 348.0 | 578.49 | 578.49 | 110.4 | 110.4 |
| 349.0 | 564.33 | 564.33 | 107.86 | 107.86 |
| 350.0 | 654.37 | 654.37 | 125.26 | 125.26 |
| 351.0 | 647.96 | 647.96 | 124.21 | 124.21 |
| 352.0 | 614.74 | 614.74 | 118.02 | 118.02 |
| 353.0 | 628.51 | 628.51 | 120.86 | 120.86 |
| 354.0 | 715.48 | 715.48 | 137.78 | 137.78 |
| 355.0 | 712.75 | 712.75 | 137.46 | 137.46 |
| 356.0 | 657.87 | 657.87 | 127.07 | 127.07 |
| 357.0 | 541.23 | 541.23 | 104.7 | 104.7 |
| 358.0 | 489.47 | 489.47 | 94.83 | 94.83 |
| 359.0 | 562.71 | 562.71 | 109.21 | 109.21 |
| 360.0 | 715.88 | 715.88 | 139.13 | 139.13 |
| 361.0 | 592.17 | 592.17 | 115.27 | 115.27 |
| 362.0 | 623.91 | 623.91 | 121.65 | 121.65 |
| 363.0 | 692.7 | 692.7 | 135.26 | 135.26 |
| 364.0 | 706.42 | 706.42 | 138.17 | 138.17 |
| 365.0 | 702.96 | 702.96 | 137.72 | 137.72 |
| 366.0 | 862.72 | 862.72 | 169.27 | 169.27 |
| 367.0 | 825.46 | 825.46 | 162.22 | 162.22 |
| 368.0 | 765.68 | 765.68 | 150.7 | 150.7 |
| 369.0 | 802.38 | 802.38 | 158.19 | 158.19 |
| 370.0 | 846.41 | 846.41 | 167.12 | 167.12 |
| 371.0 | 789.23 | 789.23 | 156.1 | 156.1 |
| 372.0 | 731.03 | 731.03 | 144.8 | 144.8 |
| 373.0 | 690.77 | 690.77 | 137.04 | 137.04 |
| 374.0 | 630.2 | 630.2 | 125.24 | 125.24 |
| 375.0 | 655.56 | 655.56 | 130.5 | 130.5 |
| 376.0 | 764.68 | 764.68 | 152.45 | 152.45 |
| 377.0 | 813.52 | 813.52 | 162.46 | 162.46 |
| 378.0 | 967.27 | 967.27 | 193.47 | 193.47 |
| 379.0 | 805.79 | 805.79 | 161.41 | 161.41 |
| 380.0 | 776.48 | 776.48 | 155.81 | 155.81 |
| 381.0 | 851.41 | 851.41 | 171.11 | 171.11 |
| 382.0 | 629.81 | 629.81 | 126.77 | 126.77 |
| 383.0 | 509.48 | 509.48 | 102.72 | 102.72 |
| 384.0 | 584.98 | 584.98 | 118.15 | 118.15 |
| 385.0 | 763.36 | 763.36 | 154.41 | 154.41 |
| 386.0 | 691.92 | 691.92 | 140.19 | 140.19 |
| 387.0 | 731.73 | 731.73 | 148.49 | 148.49 |
| 388.0 | 714.11 | 714.11 | 145.15 | 145.15 |
| 389.0 | 774.88 | 774.88 | 157.77 | 157.77 |
| 390.0 | 887.27 | 887.27 | 180.92 | 180.92 |
| 391.0 | 944.07 | 944.07 | 192.83 | 192.83 |
| 392.0 | 856.58 | 856.58 | 175.22 | 175.22 |
| 393.0 | 474.78 | 474.78 | 97.26 | 97.26 |
| 394.0 | 583.97 | 583.97 | 119.87 | 119.87 |
| 395.0 | 922.69 | 922.69 | 189.67 | 189.67 |
| 396.0 | 796.41 | 796.41 | 163.94 | 163.94 |
| 397.0 | 499.71 | 499.71 | 103.06 | 103.06 |
| 398.0 | 990.65 | 990.65 | 204.63 | 204.63 |
| 399.0 | 1153.8 | 1153.8 | 238.7 | 238.7 |
| 400.0 | 1197.9 | 1197.9 | 248.21 | 248.21 |

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**ANNEX 4**

## Effects of Spectral Response Mismatch on the Measured Erythemal Irradiance

This Annex demonstrates the effects in erythemal irradiance resulting from deviations of the spectral response of a broadband radiometer from the ideal response. To derive these results, the CIE action spectrum was modified in such a way as to meet the upper and lower limits of the desired specifications for the spectral response. Modifications were applied separately in the UVB and the UVA part of the CIE and deviations were calculated for both spectral response criteria. By weighting model derived spectra with these modified action spectra, deviations from the “true" erythemal irradiance as a function of total ozone and SZA were calculated and are shown in the following figures for the RAF and the CF ratio criteria (discussed in Section 3). In reality, such deviations can be largely reduced by applying correction factors for the actual ozone and SZA. However, for reducing the overall uncertainty it is desirable that these correction factors are as small as possible.

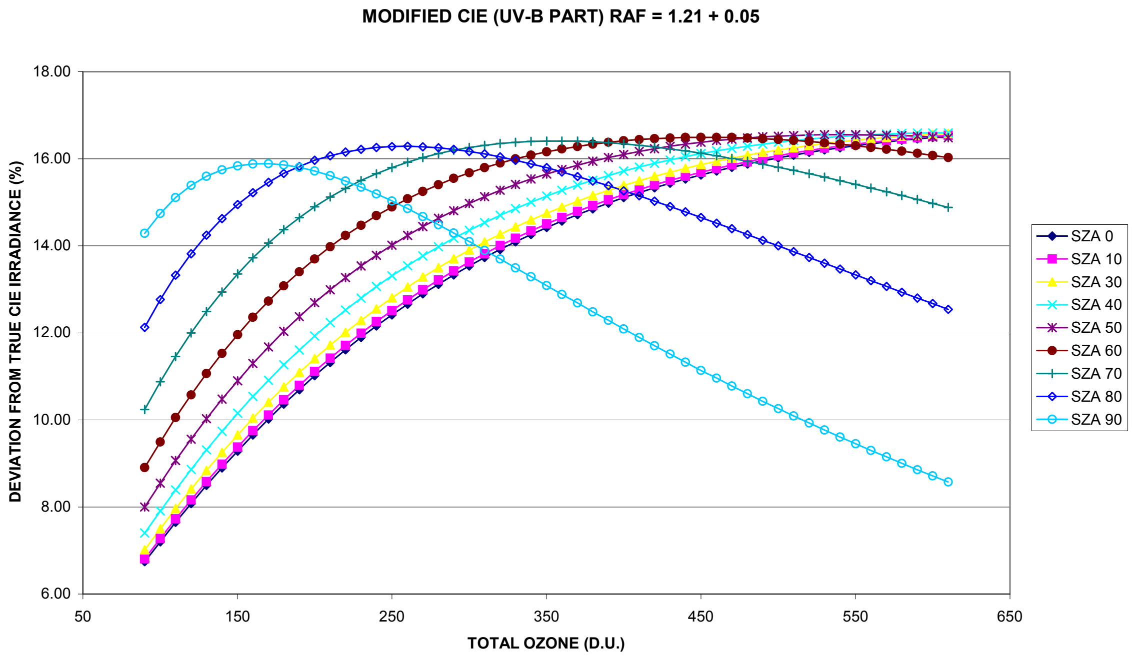

**Figure 11:** Deviation of irradiance for a modified response in the UVB from the ("true") CIE-response as a function of ozone and solar zenith angle calculated for maximal positive deviation of the desired RAF-criteria (1a in the table of specifications).

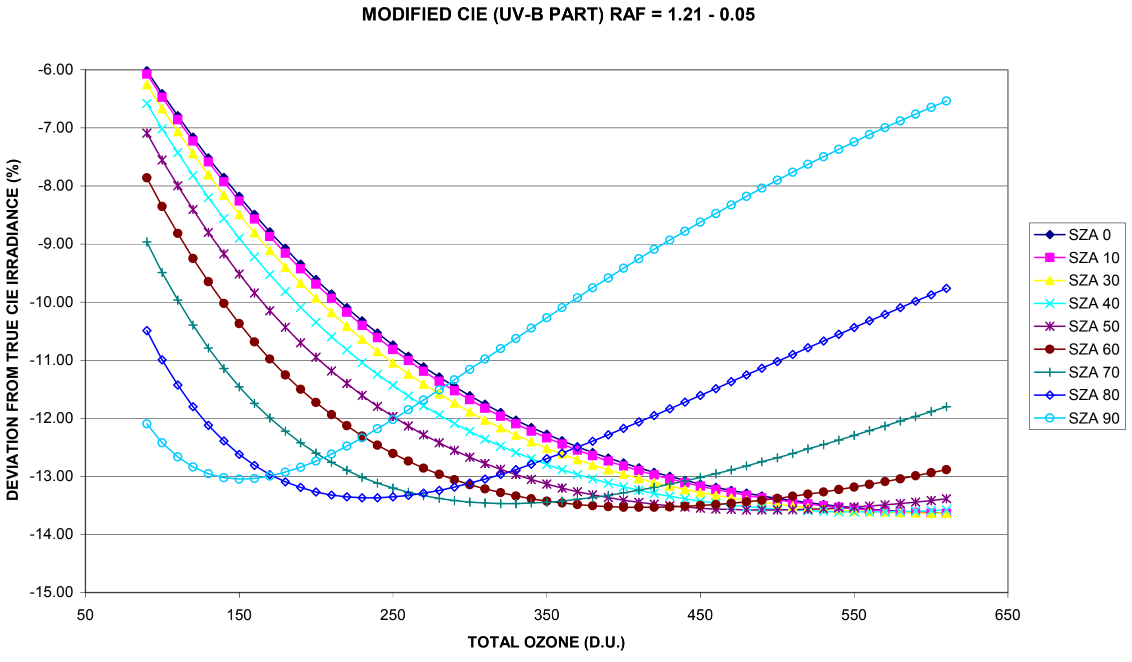

**Figure 12:** as Figure 11, for maximal negative deviation of the desired RAF-criteria.

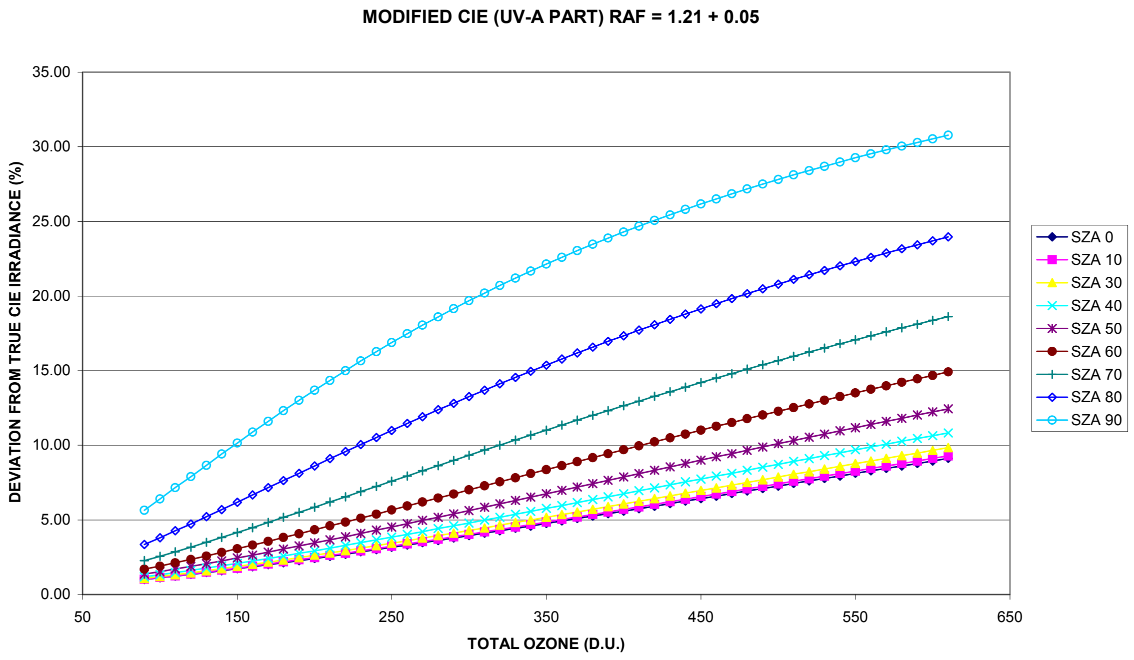

**Figure 13:** Deviation of irradiance for a modified response in the UVA from the ("true") CIE-response as a function of ozone and solar zenith angle calculated for maximal positive deviation of the desired RAF-criteria (1a in the table of specifications).

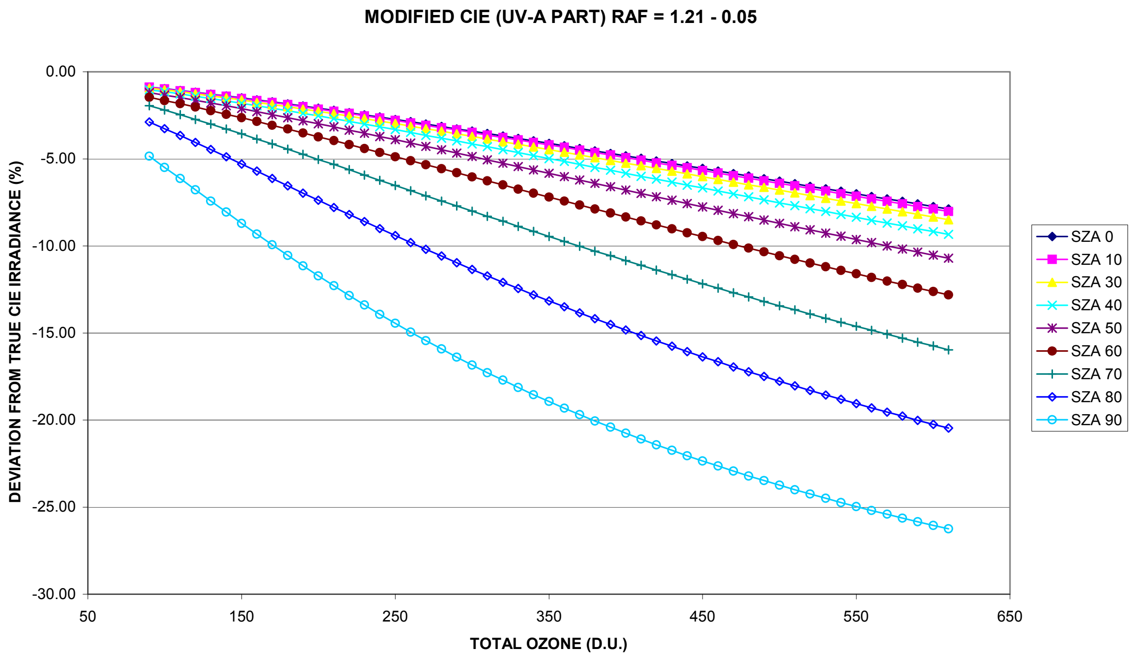

**Figure 14:** as Figure 13, for maximal negative deviation of the desired RAF-criteria.

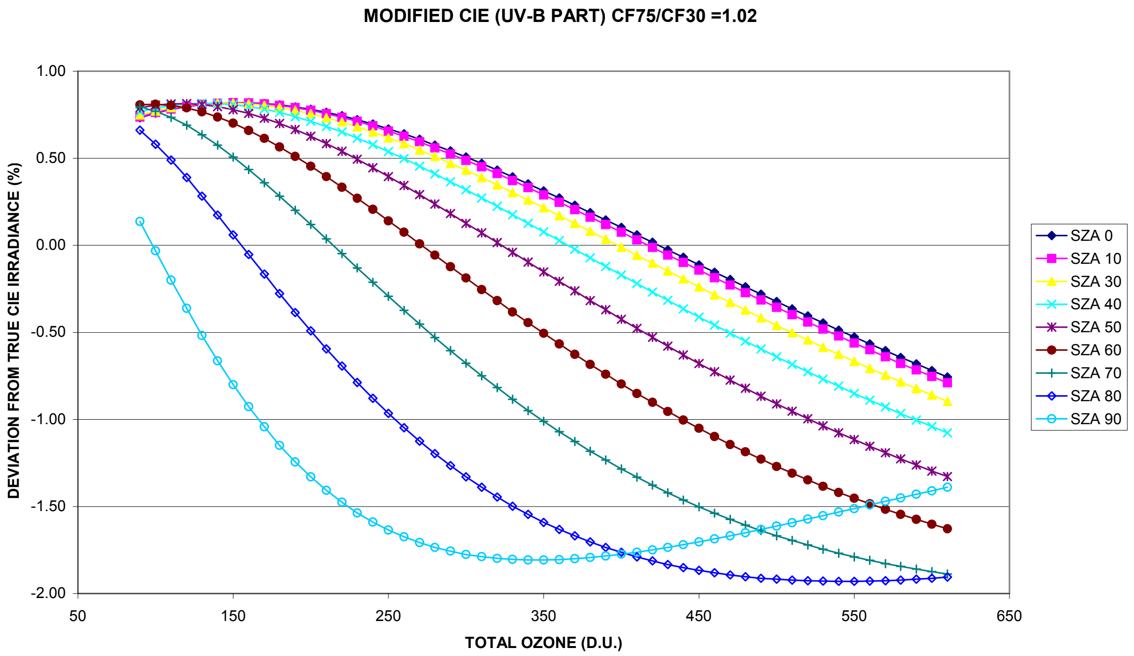

**Figure 15:** Deviation of irradiance for a modified response in the UVB from the ("true") CIE-response as a function of ozone and solar zenith angle calculated for maximal positive deviation of the desired CF-criteria (1b in the table of specifications).

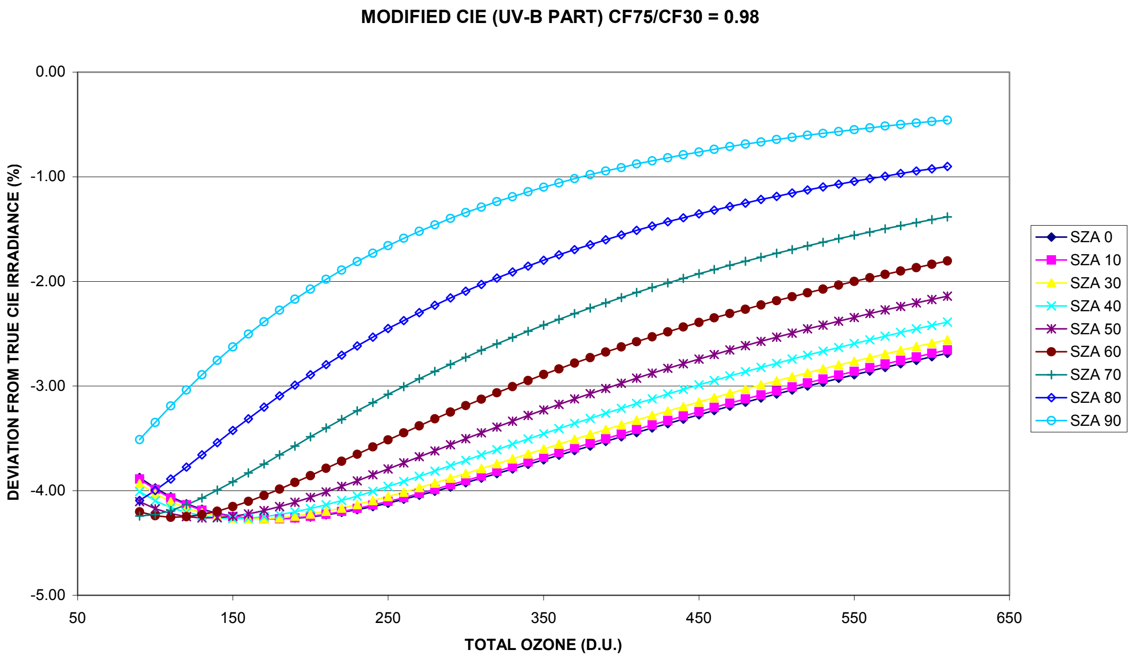

**Figure 16:** as Figure 15, for maximal negative deviation of the desired CF-criteria.

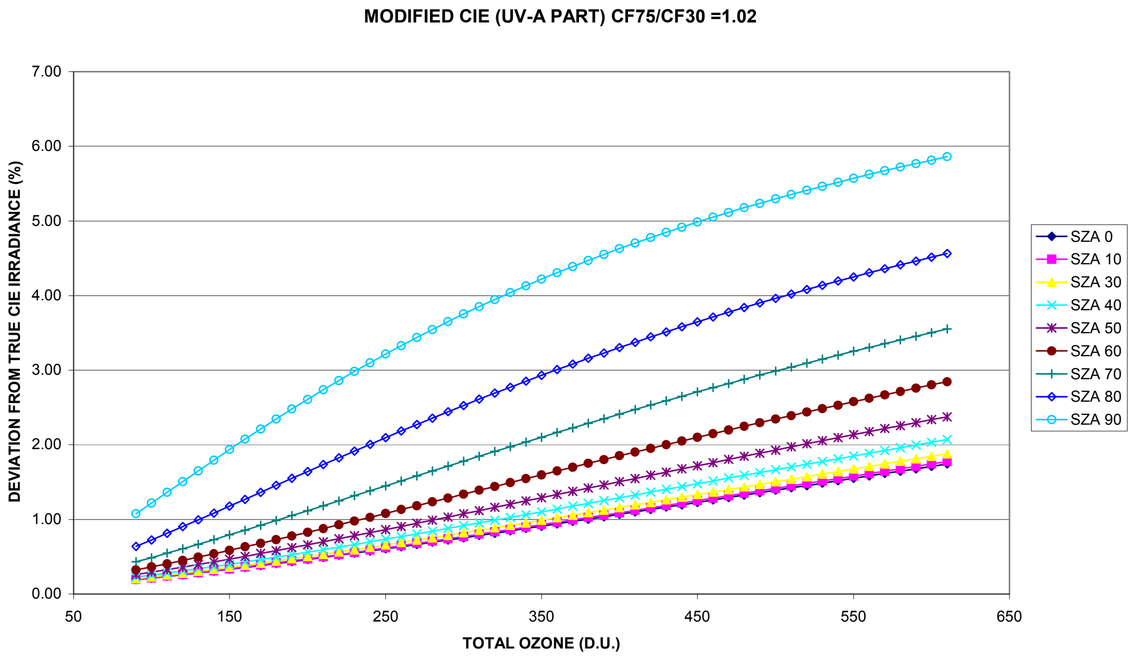

**Figure 17:** **Deviation of irradiance for a modified response in the UVA from the ("true") CIE-response as a function of ozone and solar zenith angle calculated for maximal positive deviation of the desired CF-criteria (1b in the table of specifications).**

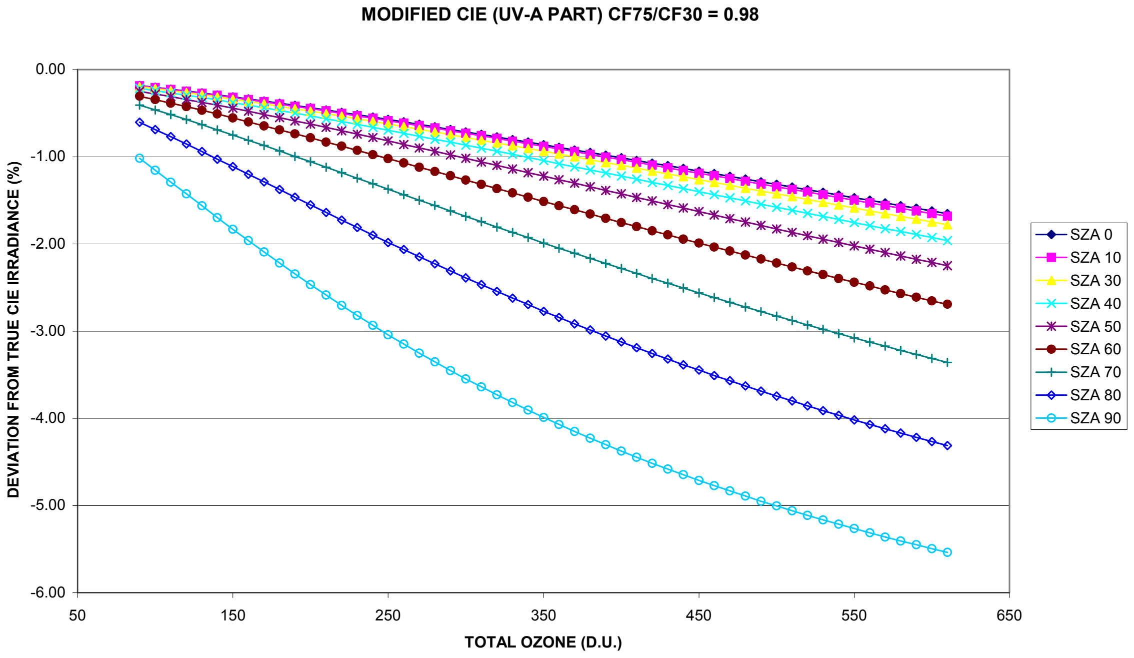

**Figure 18:** **as Figure 17, for maximal negative deviation of the desired CF-criteria.**

## References of some Freely Available Radiative Transfer Models

libRadtran - Library for Radiative Transfer

http://www.libradtran.org

LibRadtran is a freely available collection of C and Fortran functions and programmes for calculation of UV and visible radiation in the Earth's atmosphere. The model was developed by Arve Kylling and Bernhard Mayer

TUV - Tropospheric Ultraviolet and Visible Radiation Model

http://cprm.acd.ucar.edu/Models/TUV/

The TUV model was developed by Sasha Madronich and co-workers at the National Centre of Atmospheric Research.

STAR - System for Transfer of Atmospheric Radiation

http://www.meteo.physik.uni-muenchen.de/strahlung/uvrad/Star/STARinfo.htm

STAR was developed by the University of Munich to model radiation quantities and photolysis frequencies in the troposphere.

MODTRAN - Moderate Resolution Transmittance

http://www.kirtland.af.mil/afrl_vs/ir_clutter/index.asp

The MODTRAN code calculates atmospheric transmittance and radiance for frequencies from 0 to 50 000 1/cm at moderate spectral resolution.

FASTRT - Fast radiation transfer modeling

http://nadir.nilu.no/~olaeng/fastrt/fastrt.html

Online radiative transfer model based on Look-Up Tables that were calculated with RADTRAN.

## GLOBAL ATMOSPHERE WATCH REPORT SERIES

1. Final Report of the Expert Meeting on the Operation of Integrated Monitoring Programmes, Geneva, 2 -5 September 1980.

2. Report of the Third Session of the GESAMP Working Group on the Interchange of Pollutants Between the Atmosphere and the Oceans (INTERPOLL-III), Miami, USA, 27-31 October 1980.

3. Report of the Expert Meeting on the Assessment of the Meteorological Aspects of the First Phase of EMEP, Shinfield Park, U.K., 30 March - 2 April 1981.

4. Summary Report on the Status of the WMO Background Air Pollution Monitoring Network as at April 1981.

5. Report of the WMO/UNEP/ICSU Meeting on Instruments, Standardization and Measurements Techniques for Atmospheric $CO_2$, Geneva, 8-11; September 1981.

6. Report of the Meeting of Experts on BAPMoN Station Operation, Geneva, 23–26 November 1981.

7. Fourth Analysis on Reference Precipitation Samples by the Participating World Meteorological Organization Laboratories by Robert L. Lampe and John C. Puzak, December 1981.

8. Review of the Chemical Composition of Precipitation as Measured by the WMO BAPMoN by Prof. Dr. Hans-Walter Georgii, February 1982.

9. An Assessment of BAPMoN Data Currently Available on the Concentration of $CO_2$ in the Atmosphere by M.R. Manning, February 1982.

10. Report of the Meeting of Experts on Meteorological Aspects of Long-range Transport of Pollutants, Toronto, Canada, 30 November - 4 December 1981.

11. Summary Report on the Status of the WMO Background Air Pollution Monitoring Network as at May 1982.

12. Report on the Mount Kenya Baseline Station Feasibility Study edited by Dr. Russell C. Schnell.

13. Report of the Executive Committee Panel of Experts on Environmental Pollution, Fourth Session, Geneva, 27 September - 1 October 1982.

14. Effects of Sulphur Compounds and Other Pollutants on Visibility by Dr. R.F. Pueschel, April 1983.

15. Provisional Daily Atmospheric Carbon Dioxide Concentrations as Measured at BAPMoN Sites for the Year 1981, May 1983.

16. Report of the Expert Meeting on Quality Assurance in BAPMoN, Research Triangle Park, North Carolina, USA, 17-21 January 1983.

17. General Consideration and Examples of Data Evaluation and Quality Assurance Procedures Applicable to BAPMoN Precipitation Chemistry Observations by Dr. Charles Hakkarinen, July 1983.

18. Summary Report on the Status of the WMO Background Air Pollution Monitoring Network as at May 1983.

19. Forecasting of Air Pollution with Emphasis on Research in the USSR by M.E. Berlyand, August 1983.

20. Extended Abstracts of Papers to be Presented at the WMO Technical Conference on Observation and Measurement of Atmospheric Contaminants (TECOMAC), Vienna, 17-21 October 1983.

21. Fifth Analysis on Reference Precipitation Samples by the Participating World Meteorological Organization Laboratories by Robert L. Lampe and William J. Mitchell, November 1983.

22. Report of the Fifth Session of the WMO Executive Council Panel of Experts on Environmental Pollution, Garmisch-Partenkirchen, Federal Republic of Germany, 30 April - 4 May 1984 (WMO TD No. 10).

23. Provisional Daily Atmospheric Carbon Dioxide Concentrations as Measured at BAPMoN Sites for the Year 1982. November 1984 (WMO TD No. 12).

24. Final Report of the Expert Meeting on the Assessment of the Meteorological Aspects of the Second Phase of EMEP, Friedrichshafen, Federal Republic of Germany, 7-10 December 1983. October 1984 (WMO TD No. 11).

25. Summary Report on the Status of the WMO Background Air Pollution Monitoring Network as at May 1984. November 1984 (WMO TD No. 13).

26. Sulphur and Nitrogen in Precipitation: An Attempt to Use BAPMoN and Other Data to Show Regional and Global Distribution by Dr. C.C. Wallén. April 1986 (WMO TD No. 103).

27. Report on a Study of the Transport of Sahelian Particulate Matter Using Sunphotometer Observations by Dr. Guillaume A. d'Almeida. July 1985 (WMO TD No. 45).

28. Report of the Meeting of Experts on the Eastern Atlantic and Mediterranean Transport Experiment ("EAMTEX"), Madrid and Salamanca, Spain, 6-8 November 1984.

29. Recommendations on Sunphotometer Measurements in BAPMoN Based on the Experience of a Dust Transport Study in Africa by Dr. Guillaume A. d'Almeida. September 1985 (WMO TD No. 67).

30. Report of the Ad-hoc Consultation on Quality Assurance Procedures for Inclusion in the BAPMoN Manual, Geneva, 29-31 May 1985.

31. Implications of Visibility Reduction by Man-Made Aerosols (Annex to No. 14) by R.M. Hoff and L.A. Barrie. October 1985 (WMO TD No. 59).

32. Manual for BAPMoN Station Operators by E. Meszaros and D.M. Whelpdale. October 1985 (WMO TD No. 66).

33. Man and the Composition of the Atmosphere: BAPMoN - An international programme of national needs, responsibility and benefits by R.F. Pueschel, 1986.

34. Practical Guide for Estimating Atmospheric Pollution Potential by Dr. L.E. Niemeyer. August 1986 (WMO TD No. 134).

35. Provisional Daily Atmospheric $CO_2$ Concentrations as Measured at BAPMoN Sites for the Year 1983. December 1985 (WMO TD No. 77).

36. Global Atmospheric Background Monitoring for Selected Environmental Parameters. BAPMoN Data for 1984. Volume I: Atmospheric Aerosol Optical Depth. October 1985 (WMO TD No. 96).

37. Air-Sea Interchange of Pollutants by R.A. Duce. September 1986 (WMO TD No. 126).

38. Summary Report on the Status of the WMO Background Air Pollution Monitoring Network as at 31 December 1985. September 1986 (WMO TD No. 136).

39. Report of the Third WMO Expert Meeting on Atmospheric Carbon Dioxide Measurement Techniques, Lake Arrowhead, California, USA, 4-8 November 1985. October 1986.

40. Report of the Fourth Session of the CAS Working Group on Atmospheric Chemistry and Air Pollution, Helsinki, Finland, 18-22 November 1985. January 1987.

41. Global Atmospheric Background Monitoring for Selected Environmental Parameters. BAPMoN Data for 1982, Volume II: Precipitation chemistry, continuous atmospheric carbon dioxide and suspended particulate matter. June 1986 (WMO TD No. 116).

42. Scripps reference gas calibration system for carbon dioxide-in-air standards: revision of 1985 by C.D. Keeling, P.R. Guenther and D.J. Moss. September 1986 (WMO TD No. 125).

43. Recent progress in sunphotometry (determination of the aerosol optical depth). November 1986.

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45. Proceedings of the International Symposium on Integrated Global Monitoring of the State of the Biosphere (Volumes I-IV), Tashkent, USSR, 14-19 October 1985. December 1986 (WMO TD No. 151).

46. Provisional Daily Atmospheric Carbon Dioxide Concentrations as Measured at BAPMoN Sites for the Year 1984. December 1986 (WMO TD No. 158).

47. Procedures and Methods for Integrated Global Background Monitoring of Environmental Pollution by F.Ya. Rovinsky, USSR and G.B. Wiersma, USA. August 1987 (WMO TD No. 178).

48. Meeting on the Assessment of the Meteorological Aspects of the Third Phase of EMEP IIASA, Laxenburg, Austria, 30 March - 2 April 1987. February 1988.

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50. Provisional Daily Atmospheric Carbon Dioxide Concentrations as Measured at BAPMoN Sites for the Year 1985. December 1987 (WMO TD No. 198).

51. Report of the NBS/WMO Expert Meeting on Atmospheric $CO_2$ Measurement Techniques, Gaithersburg, USA, 15-17 June 1987. December 1987.

52. Global Atmospheric Background Monitoring for Selected Environmental Parameters. BAPMoN Data for 1985. Volume I: Atmospheric Aerosol Optical Depth. September 1987.

53. WMO Meeting of Experts on Strategy for the Monitoring of Suspended Particulate Matter in BAPMoN - Reports and papers presented at the meeting, Xiamen, China, 13-17 October 1986. October 1988.

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55. Summary Report on the Status of the WMO Background Air Pollution Monitoring Network as at 31 December 1987 (WMO TD No. 284).

56. Report of the First Session of the Executive Council Panel of Experts/CAS Working Group on Environmental Pollution and Atmospheric Chemistry, Hilo, Hawaii, 27-31 March 1988. June 1988.

57. Global Atmospheric Background Monitoring for Selected Environmental Parameters. BAPMoN Data for 1986, Volume I: Atmospheric Aerosol Optical Depth. July 1988.

58. Provisional Daily Atmospheric Carbon Dioxide Concentrations as measured at BAPMoN sites for the years 1986 and 1987 (WMO TD No. 306).

59. Extended Abstracts of Papers Presented at the Third International Conference on Analysis and Evaluation of Atmospheric $CO_2$ Data - Present and Past, Hinterzarten, Federal Republic of Germany, 16-20 October 1989 (WMO TD No. 340).

60. Global Atmospheric Background Monitoring for Selected Environmental Parameters. BAPMoN Data for 1984 and 1985, Volume II: Precipitation chemistry, continuous atmospheric carbon dioxide and suspended particulate matter.

61. Global Atmospheric Background Monitoring for Selected Environmental Parameters. BAPMoN Data for 1987 and 1988, Volume I: Atmospheric Aerosol Optical Depth.

62. Provisional Daily Atmospheric Carbon Dioxide Concentrations as measured at BAPMoN sites for the year 1988 (WMO TD No. 355).

63. Report of the Informal Session of the Executive Council Panel of Experts/CAS Working Group on Environmental Pollution and Atmospheric Chemistry, Sofia, Bulgaria, 26 and 28 October 1989.

64. Report of the consultation to consider desirable locations and observational practices for BAPMoN stations of global importance, Bermuda Research Station, 27-30 November 1989.

65. Report of the Meeting on the Assessment of the Meteorological Aspects of the Fourth Phase of EMEP, Sofia, Bulgaria, 27 and 31 October 1989.

66. Summary Report on the Status of the WMO Global Atmosphere Watch Stations as at 31 December 1990 (WMO TD No. 419).

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68. Global Atmospheric Background Monitoring for Selected Environmental Parameters. BAPMoN Data For 1989, Volume I: Atmospheric Aerosol Optical Depth.

69. Provisional Daily Atmospheric Carbon Dioxide Concentrations as measured at Global Atmosphere Watch (GAW)-BAPMoN sites for the year 1989 (WMO TD No. 400).

70. Report of the Second Session of EC Panel of Experts/CAS Working Group on Environmental Pollution and Atmospheric Chemistry, Santiago, Chile, 9-15 January 1991 (WMO TD No. 633).

71. Report of the Consultation of Experts to Consider Desirable Observational Practices and Distribution of GAW Regional Stations, Halkidiki, Greece, 9-13 April 1991 (WMO TD No. 433).

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74. Report of the Experts Meeting on Aerosol Physics and Chemistry, Hampton, Virginia, 30 to 31 May 1991 (WMO TD No. 439).

75. Provisional Daily Atmospheric Carbon Dioxide Concentrations as measured at Global Atmosphere Watch (GAW)-BAPMoN sites for the year 1990 (WMO TD No. 447).

76. The International Global Aerosol Programme (IGAP) Plan: Overview (WMO TD No. 445).

77. Report of the WMO Meeting of Experts on Carbon Dioxide Concentration and Isotopic Measurement Techniques, Lake Arrowhead, California, 14-19 October 1990.

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80. Report of the WMO Meeting of Experts on the Quality Assurance Plan for the GAW, Garmisch-Partenkirchen, Germany, 26-30 March 1992 (WMO TD No. 513).

81. Report of the Second Meeting of Experts to Assess the Response to and Atmospheric Effects of the Kuwait Oil Fires, Geneva, Switzerland, 25-29 May 1992 (WMO TD No. 512).

82. Global Atmospheric Background Monitoring for Selected Environmental Parameters BAPMoN Data for 1991, Volume I: Atmospheric Aerosol Optical Depth (WMO TD No. 518).

83. Report on the Global Precipitation Chemistry Programme of BAPMoN (WMO TD No. 526).

84. Provisional Daily Atmospheric Carbon Dioxide Concentrations as measured at GAW-BAPMoN sites for the year 1991 (WMO TD No. 543).

85. Chemical Analysis of Precipitation for GAW: Laboratory Analytical Methods and Sample Collection Standards by Dr Jaroslav Santroch (WMO TD No. 550).

86. The Global Atmosphere Watch Guide, 1993 (WMO TD No. 553).

87. Report of the Third Session of EC Panel/CAS Working Group on Environmental Pollution and Atmospheric Chemistry, Geneva, 8-11 March 1993 (WMO TD No. 555).

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89. 4th International Conference on $CO_2$ (Carqueiranne, France, 13-17 September 1993) (WMO TD No. 561).

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91. Extended Abstracts of Papers Presented at the WMO Region VI Conference on the Measurement and Modelling of Atmospheric Composition Changes Including Pollution Transport, Sofia, 4 to 8 October 1993 (WMO TD No. 563).

92. Report of the Second WMO Meeting of Experts on the Quality Assurance/Science Activity Centres of the Global Atmosphere Watch, Garmisch-Partenkirchen, 7-11 December 1992 (WMO TD No. 580).

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94. Report on the Measurements of Atmospheric Turbidity in BAPMoN (WMO TD No. 603).

95. Report of the WMO Meeting of Experts on UVB Measurements, Data Quality and Standardization of UV Indices, Les Diablerets, Switzerland, 25-28 July 1994 (WMO TD No. 625).

96. Global Atmospheric Background Monitoring for Selected Environmental Parameters WMO GAW Data for 1993, Volume I: Atmospheric Aerosol Optical Depth.

97. Quality Assurance Project Plan (QAPjP) for Continuous Ground Based Ozone Measurements (WMO TD No. 634).

98. Report of the WMO Meeting of Experts on Global Carbon Monoxide Measurements, Boulder, USA, 7-11 February 1994 (WMO TD No. 645).

99. Status of the WMO Global Atmosphere Watch Programme as at 31 December 1993 (WMO TD No. 636).

100. Report of the Workshop on UVB for the Americas, Buenos Aires, Argentina, 22-26 August 1994.

101. Report of the WMO Workshop on the Measurement of Atmospheric Optical Depth and Turbidity, Silver Spring, USA, 6-10 December 1993, (edited by Bruce Hicks) (WMO TD No. 659).

102. Report of the Workshop on Precipitation Chemistry Laboratory Techniques, Hradec Kralove, Czech Republic, 17-21 October 1994 (WMO TD No. 658).

103. Report of the Meeting of Experts on the WMO World Data Centres, Toronto, Canada, 17 - 18 February 1995, (prepared by Edward Hare) (WMO TD No. 679).

104. Report of the Fourth WMO Meeting of Experts on the Quality Assurance/Science Activity Centres (QA/SACs) of the Global Atmosphere Watch, jointly held with the First Meeting of the Coordinating Committees of IGAC-GLONET and IGAC-ACE, Garmisch-Partenkirchen, Germany, 13 to 17 March 1995 (WMO TD No. 689).

105. Report of the Fourth Session of the EC Panel of Experts/CAS Working Group on Environmental Pollution and Atmospheric Chemistry (Garmisch, Germany, 6-11 March 1995) (WMO TD No. 718).

106. Report of the Global Acid Deposition Assessment (edited by D.M. Whelpdale and M-S. Kaiser) (WMO TD No. 777).

107. Extended Abstracts of Papers Presented at the WMO-IGAC Conference on the Measurement and Assessment of Atmospheric Composition Change (Beijing, China, 9-14 October 1995) (WMO TD No. 710).

108. Report of the Tenth WMO International Comparison of Dobson Spectrophotometers (Arosa, Switzerland, 24 July - 4 August 1995).

109. Report of an Expert Consultation on 85Kr and 222Rn: Measurements, Effects and Applications (Freiburg, Germany, 28-31 March 1995) (WMO TD No. 733).

110. Report of the WMO-NOAA Expert Meeting on GAW Data Acquisition and Archiving (Asheville, NC, USA, 4-8 November 1995) (WMO TD No. 755).

111. Report of the WMO-BMBF Workshop on VOC Establishment of a “World Calibration/Instrument Intercomparison Facility for VOC” to Serve the WMO Global Atmosphere Watch (GAW) Programme (Garmisch-Partenkirchen, Germany, 17-21 December 1995) (WMO TD No. 756).

112. Report of the WMO/STUK Intercomparison of Erythemally-Weighted Solar UV Radiometers, Spring/Summer 1995, Helsinki, Finland (WMO TD No. 781).

112A. Report of the WMO/STUK ’95 Intercomparison of broadband UV radiometers: a small-scale follow-up study in 1999, Helsinki, 2001, Addendum to GAW Report No. 112.

113. The Strategic Plan of the Global Atmosphere Watch (GAW) (WMO TD No. 802).

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117. Report and Proceedings of the Workshop on the Assessment of EMEP Activities Concerning Heavy Metals and Persistent Organic Pollutants and their Further Development (Moscow, Russian Federation, 24-26 September 1996) (Volumes I and II) (WMO TD No. 806).

118. Report of the International Workshops on Ozone Observation in Asia and the Pacific Region (IWOAP, IWOAP-II), (IWOAP, 27 February-26 March 1996 and IWOAP-II, 20 August-18 September 1996) (WMO TD No. 827).

119. Report on BoM/NOAA/WMO International Comparison of the Dobson Spectrophotometers (Perth Airport, Perth, Australia, 3-14 February 1997), (prepared by Robert Evans and James Easson) (WMO TD No. 828).

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126. Guidelines for Site Quality Control of UV Monitoring (lead author A.R. Webb) (WMO TD No. 884).

127. Report of the WMO-WHO Meeting of Experts on Standardization of UV Indices and their Dissemination to the Public (Les Diablerets, Switzerland, 21-25 July 1997) (WMO TD No. 921).

128. The Fourth Biennial WMO Consultation on Brewer Ozone and UV Spectrophotometer Operation, Calibration and Data Reporting, (Rome, Italy, 22-25 September 1996) (WMO TD No. 918).

129. Guidelines for Atmospheric Trace Gas Data Management (Ken Masarie and Pieter Tans), 1998 (WMO TD No. 907).

130. Jülich Ozone Sonde Intercomparison Experiment (JOSIE, 5 February to 8 March 1996), (H.G.J. Smit and D. Kley) (WMO TD No. 926).

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132. Report of the Ninth WMO Meeting of Experts on Carbon Dioxide Concentration and Related Tracer Measurement Techniques (Edited by Roger Francey), (Aspendale, Vic., Australia).

133. Workshop on Advanced Statistical Methods and their Application to Air Quality Data Sets (Helsinki, 14-18 September 1998) (WMO TD No. 956).

134. Guide on Sampling and Analysis Techniques for Chemical Constituents and Physical Properties in Air and Precipitation as Applied at Stations of the Global Atmosphere Watch. Carbon Dioxide (WMO TD No. 980).

135. Sixth Session of the EC Panel of Experts/CAS Working Group on Environmental Pollution and Atmospheric Chemistry (Zurich, Switzerland, 8-11 March 1999) (WMO TD No.1002).

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140. WMO/CEOS Report on a Strategy for Integrating Satellite and Ground-based Observations of Ozone (WMO TD No. 1046).

141. Report of the LAP/COST/WMO Intercomparison of Erythemal Radiometers Thessaloniki, Greece, 13-23 September 1999) (WMO TD No. 1051).

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143. Global Atmosphere Watch Measurements Guide (WMO TD No. 1073).

144. Report of the Seventh Session of the EC Panel of Experts/CAS Working Group on Environmental Pollution and Atmospheric Chemistry and the GAW 2001 Workshop (Geneva, Switzerland, 2 to 5 April 2001) (WMO TD No. 1104).

145. WMO GAW International Comparisons of Dobson Spectrophotometers at the Meteorological Observatory Hohenpeissenberg, Germany (21 May – 10 June 2000, MOHp2000-1), 23 July – 5 August 2000, MOHp2000-2), (10 – 23 June 2001, MOHp2001-1) and (8 to 21 July 2001, MOHp2001-2). Prepared by Ulf Köhler (WMO TD No. 1114).

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148. Report of the Eleventh WMO/IAEA Meeting of Experts on Carbon Dioxide Concentration and Related Tracer Measurement Techniques (Tokyo, Japan, 25-28 September 2001) (WMO TD No 1138).

149. Comparison of Total Ozone Measurements of Dobson and Brewer Spectrophotometers and Recommended Transfer Functions (prepared by J. Staehelin, J. Kerr, R. Evans and K. Vanicek) (WMO TD No. 1147).

150. Updated Guidelines for Atmospheric Trace Gas Data Management (Prepared by Ken Maserie and Pieter Tans (WMO TD No. 1149).

151. Report of the First CAS Working Group on Environmental Pollution and Atmospheric Chemistry (Geneva, Switzerland, 18-19 March 2003) (WMO TD No. 1181).

152. Current Activities of the Global Atmosphere Watch Programme (as presented at the 14th World Meteorological Congress, May 2003). (WMO TD No. 1168).

153. WMO/GAW Aerosol Measurement Procedures: Guidelines and Recommendations. (WMO TD No. 1178).

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156. Addendum for the Period 2005-2007 to the Strategy for the Implementation of the Global Atmosphere Watch Programme (2001-2007), GAW Report No. 142 (WMO TD No. 1209).

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158. JOSIE-2000 Jülich Ozone Sonde Intercomparison Experiment 2000. The 2000 WMO International Intercomparison of Operating Procedures for ECC-ozone Sondes at the Environmental Simulation Facility at Jülich (Prepared by Herman G.J. Smit and Wolfgang Straeter) (WMO TD No. 1225).

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160. Manual for the GAW Precipitation Chemistry Programme (Guidelines, Data Quality Objectives and Standard Operating Procedures) (WMO TD No. 1251).

161. 12th WMO/IAEA Meeting of Experts on Carbon Dioxide Concentration and Related Tracers Measurement Techniques (Toronto, Canada, 15-18 September 2003) (Edited by Doug Worthy and Lin Huang) (WMO TD No. 1275).

162. WMO/GAW Experts Workshop on a Global Surface-Based Network for Long Term Observations of Column Aerosol Optical Properties, Davos, Switzerland, 8-10 March 2004 (edited by U. Baltensperger, L. Barrie and C. Wehrli) (WMO TD No. 1287).

163. World Meteorological Organization Activities in Support of the Vienna Convention on Protection of the Ozone Layer (WMO TD No. 1288).