For more information, please contact:

World Meteorological Organization

Research Department

Atmospheric Research and Environment Branch

7 bis, avenue de la Paix – P.O. Box 2300 – CH 1211 Geneva 2 – Switzerland

Tel.: +41 (0) 22 730 81 11 – Fax: +41 (0) 22 730 81 81

E-mail: AREP-MAIL@wmo.int – Website: http://www.wmo.int/pages/prog/arep/index_en.html

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GAW Report No. 198

Data Quality Objectives (DQO) for Solar Ultraviolet Radiation Measurements (Part I)

Chairperson, Publications Board
World Meteorological Organization (WMO)
7 bis, avenue de la Paix
P.O. Box 2300
CH-1211 Geneva 2, Switzerland

Tel.: +41 (0) 22 730 84 03
Fax: +41 (0) 22 730 80 40
E-mail: Publications@wmo.int

WORLD METEOROLOGICAL ORGANIZATION
GLOBAL ATMOSPHERE WATCH

DATA QUALITY OBJECTIVES (DQO) FOR SOLAR ULTRAVIOLET RADIATION MEASUREMENTS (Part I)

Addendum to WMO/GAW Report No. 146

Quality Assurance in Monitoring Solar Ultraviolet Radiation: State of the Art

World
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April 2011

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1. INTRODUCTION

Solar ultraviolet (UV) radiation can be measured by several different classes of instrument and the data applied to a range of objectives. It is crucial to match the instrument employed to the intended objective, and to ensure that sufficient facilities are available to support the objective in terms of personnel and QA/QC requirements. The technical specifications of the different types of instrument for measuring solar UV radiation are detailed in the GAW series of publications "Instruments to measure solar ultraviolet radiation" (WMO/GAW Reports 125, scanning spectral instruments, and 164, broadband instruments), which should be read in conjunction with the following DQOs. Quality control and quality assurance issues are covered in a further two GAW publications (WMO/GAW Report 126 and 146).

The four types of instrument available for solar UV measurement are scanning spectroradiometers, broadband, multifilter and array spectroradiometers. Spectral instruments provide high resolution spectral data that should cover the range 290-325 nm as a minimum, and ideally the full solar UV region 290-400nm. The spectral bandwidth should be less than 1 nm full width at half maximum and tolerances on other aspects of instrument performance are detailed in (1). Spectral instruments are the most costly, complex and demanding of those available, but provide the most versatile data. Note that here, and in (1) we only refer to scanning-spectroradiometers and not to the solid state instruments that have recently become available (array spectroradiometers). In this document, only DQOs for scanning spectroradiometers and broadband instruments are considered, multi-filter and array spectroradiometers will be covered in a future addendum.

Broadband radiometers, for the purposes of this document, are taken as those instruments that measure the total erythemal (or "sunburning") irradiance (type B-1). These are the most common broadband UV instruments, although there are other designs that measure, for example, total UVA (315 – 400 nm) radiation. A broadband erythemal radiometer has a response spectrum that approximates that of the erythema (sunburn) action spectrum (7). Deviations between the actual meter response and the true erythemal action spectrum can be accounted for in the calibration process (2). The UV index (8) is derived directly from the erythemal irradiance. The relative simplicity of broadband instruments means that they are cheaper to purchase and have fewer operational problems than scanning spectroradiometers. However, their maintenance and QA/QC can introduce substantial additional cost.

Multifilter radiometers combine some of the properties of both broadband and spectral instruments (3). They provide coarse spectral data by employing several different channels to detect radiation in a number of wavebands of typical width between 2 and 10 nm. They are essentially a series of narrowband radiometers packaged together with a common input optic, power supply and data acquisition facility. The spectral information available makes the data more versatile than that of a broadband radiometer, but they cannot match the detail and applications possible with a scanning spectroradiometer. Routine operation, and QA/QC issues are a combination of those required for spectral and broadband instrument. At the time of writing the details of these instruments have not been finalised and will follow with the publication of (3).

2. OBJECTIVES

General objectives for measuring solar ultraviolet irradiance are discussed below. There are numerous other research objectives that may require special consideration (e.g.: a change of input optic), or that may use data gathered during routine monitoring for a new application, but this document discusses the objectives applicable to a global monitoring programme.

Objectives for monitoring solar UV radiation:

1. To establish a UV climatology by long-term monitoring, e.g. within a network.
2. To detect trends in global UV irradiance.

3. To provide datasets for specific process studies (e.g.: atmospheric, biological and material sciences).
4. To validate radiative transfer models and/or satellite derived UV irradiance at the Earth's surface.
5. To understand geographic differences in global UV irradiance.
6. To gain information about actual UV levels and their diurnal and seasonal variability.
7. To provide data for public information and awareness (e.g. UV index).

Many of these general objectives have to be modified, or qualified, by the type of instrument used e.g. to gain information about actual spectral / erythemal UV levels.

Not all instruments are suited to all of the objectives e.g. broadband instruments are not ideal for trend detection unless the expected trends are large. There are, however, additional objectives that may be assigned to instruments types deployed together, for example for broadband (and multifilter) instruments:

8. To supplement spectral UV measurements (e.g. temporal and spatial interpolation, interpretation of cloud effects).
9. To help in quality control of spectral UV measurements.

Note that data gathered at a site will be unique to that site, and may or may not represent the immediate area or local region, depending on the homogeneity of the surroundings. In some cases the site may be chosen because it represents a special case, or is an extreme example (e.g.: top of mountain). However, the site should still be able to represent the expected measurement situation for solar radiation i.e. the instrument (or its input optics) should not be shaded at anytime and should have an unobstructed 2 pi field of view when the detecting surface is flat and horizontal. Where the latter situation is not possible the imperfect horizon should be mapped and the radiation loss assessed; the losses will be small for obstructions subtending small angles to the optics. A full description of the site should be available with the data – guidance on sitting an instrument and describing the site are available in (5).

3. MATCHING OBJECTIVES AND INSTRUMENTS

Objectives 1, 5, 6 and 7 above can be achieved using any class of instrument, but it is necessary to accomplish a minimum requirement in quality. Insights into the causes of geographical differences, diurnal or seasonal variability may be lost with a lack of spectral information, but a well maintained instrument of any type still provides valuable information about the UV climatology at a site.

No broadband instrument available at the time of preparation of this document will meet all the desired specifications, therefore, some guidance in selecting between the currently available instruments according to the application is provided in Table I, (extracted from (2)).

Table I - 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	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		++	+	+		+	+	+
Leveling		++	+	++		+	++	+
Sampling frequency		+		++			++	+

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

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

Combining or comparing data from more than one site requires a greater emphasis to be placed on quality assurance (6) than when assessing a single site. Combining data from different instrument classes is possible at the loss of spectral resolution. Erythemal UV irradiance can be derived from both spectral and multifilter instruments, making this (and the UV index) a quantity common to all instruments. By corollary, the simpler broadband instruments can be used to help identify problems in the more complex spectral data that may otherwise go undetected (objective 9).

The second listed objective, trend detection, is the most demanding goal of UV monitoring. Even at a fixed site the incident UV is influenced by cloud, ozone, aerosol and albedo, all of which can vary tremendously from day to day and year to year, while being within normal ranges. Detecting a true trend, especially a small trend (all that is expected in most regions of the world) against such a background is extremely demanding. Any trend due to ozone depletion / recovery would be most obvious at the short wavelengths most affected by ozone, thus spectral instruments are most suited to this task. The instrument specifications (1) and the QA/QC requirements (5, 6) necessary to enable detection of small trends are also very stringent and must be maintained over a prolonged period to justify trend detection. A useful but ambitious goal is to attempt to detect a change in spectral UV irradiance resulting from a 1% change in total ozone column. In order to detect this change, the wavelength alignment accuracy must be significantly better than ±0.05nm, the detection threshold must be in the order of 10^{-6} W m^{-2} nm^{-1} or lower and the accuracy of the absolute calibration must be at least ± 5%. (1). This objective is thus the most exacting and not easily achieved. Broadband radiometers might be suited to this task if large trends were to occur, or trends that were spectrally flat (e.g.: due to changes in cloud cover). Otherwise, the role of the broadband radiometer in trend detection is found as a supporting instrument (objective 9) in helping to maintain the tight quality control necessary for the task.

Providing datasets for process studies or satellite validation (objective 3 and 4) is again best served by spectral instruments. For the validation of radiative transfer models the accuracy of spectral measurements must be comparable to the accuracy needed for trend detection (1).

The spectral data is necessary for identifying or disentangling processes, and provides the most stringent test of satellite retrievals. Nevertheless, there is also an important role for the radiometers in conjunction with the detailed spectral data. One of the disadvantages of spectral instruments is the time taken to make a measurement (for the scanning instruments: diode array and CCD devices do not have this problem, but as single monochromators they suffer from straylight problems in the UVB). They are also difficult to deploy in large numbers because of their demanding operational requirements. Thus the simpler radiometers with their rapid sampling capabilities and easier deployment can be used to help interpret the spectral data, or interpolate either spatially or temporally between spectra (objective 8).

For any of the above mentioned objectives, data collection needs to be automated and all weather.

Further specifications for, and justifications of, the instrument requirements for each objective are provided in the Instrument document series (1 - 4).

All Objectives

While different instrument types may be either required or selected for the different objectives, all objectives and instrument types have a few common operational requirements:

a) The instrument, of whatever type, should be operated according to GAW Standard Operating Procedures, or Operating Guidelines, where they exist. Where such documentation does not exist, relevant parts of other appropriate Guidelines or SOPs should be applied (e.g.: details on cleaning of input optics, or updating of logging time clocks, is common to all types of UV measurement), in addition to following manufacturer's guidance on maintenance and upkeep of the equipment.

Note that good routine maintenance underpins reliable long-term data.

b) The calibration history of the instrument should be maintained, and the calibration clearly traceable to an accepted authoritative source. Ideally, this should be one of the Regional Calibration Centres, now available for ultraviolet measurements in North America (CUCF, Boulder, Colorado, since 1993) and Europe (WRC/PMOD, Davos, Switzerland, since 2008). However, we recognise that it is not, and has not, always been possible to utilise one of these centres. Thus, every effort should be made to make use of regional intercomparisons, comparison of calibration lamps, and similar exercises to assist in maintaining quality assurance of the data (6). Where instruments (spectroradiometers) are calibrated with standards of spectral irradiance the traceability of the lamps should be known, including the National Standards Laboratory to which the standard reverts, and the number of steps from the NSL to the lamp used in the calibration, together with the associated uncertainty.

3.1 Objective 1: To establish a UV climatology by long-term monitoring, e.g. within a network

The minimum requirements to accomplish this objective are listed below, for each type of instrument.

3.1.1 Scanning Spectroradiometer

Specifications Scanning Spectroradiometer Type S-1

Table II - Specifications scanning spectroradiometer instruments type S-1 (1)

Quantity	Quality
Cosine error§	(a) < ±5 % for incidence angles <60° (b) < ±5 % to integrated isotropic radiance
Minimum spectral range	290 - 325 nm+
Bandwidth (FWHM)	< 1 nm
Wavelength precision	< ±0.05 nm
Wavelength accuracy	< ±0.1 nm
Slit function	< 10^{-3} of maximum at 2.5·FWHM away from centre#
Sampling wavelength interval	< FWHM
Maximum irradiance	> 1 W m^{-2} nm^{-1} at 325 nm and, if applicable, 2 W m^{-2} nm^{-1} at 400 nm (noon maximum)
Detection threshold	< $5 \cdot 10^{-5}$ W m^{-2} nm^{-1} (for SNR = 1 at 1 nm FWHM)
Stray light	< $5 \cdot 10^{-4}$ W m^{-2} nm^{-1} when the instrument is exposed to the sun at minimum solar zenith angle
Instrument temperature	Monitored and sufficiently stable to maintain overall instrument stability
Scan time	< 10 minutes per spectrum, e.g., for ease of comparison
Overall calibration uncertainty*	< ±10% (unless limited by detection threshold)
Scan date and time	Recorded with each spectrum such that timing is known to within 10 seconds at each wavelength

§ Smaller cosine errors would be desirable, and it is now possible to get input optics with very small cosine errors for those instruments for which a fibre optic input is usual. For details and definition see WMO/GAW Report 125.

* The overall calibration uncertainty includes all uncertainties associated with the irradiance calibration (for example: uncertainty of the standard lamps, transfer uncertainties, alignment errors during calibration, and drift of the instrument between calibrations).

+ An extension to longer wavelengths is desirable for the establishment of an UV- climatology with respect to biological applications.

Ancillary Measurements

a) Required
- Independent measurements of global irradiance insensitive to ozone absorption, e.g., measurements of short wave global irradiance with a pyranometer.

b) Desirable
- Direct normal spectral irradiance or diffuse spectral irradiance.
- Total ozone column, e.g., derived from measurements of direct normal spectral irradiance.
- Erythemally weighted irradiance, measured with a broad-band radiometer.
- Atmospheric pressure.
- Cloud information (amount, type, height, etc).
- Illuminance, measured with a luxmeter.
- Direct irradiance at normal incidence measured with a pyrheliometer.
- Aerosol related properties (e.g.: Aerosol Optical Depth, visibility).

Data Frequency

*A*t least one scan per hour, including a scan at local solar noon.

Completeness

The number of missing data and their distribution are important, particularly when calculating mean values. For example, calculating monthly mean values, the number of complete days is important, but also the distribution of the missing or incomplete days (i.e.: all at the beginning or the end of the months, or evenly distributed, etc). There is not an established criterion for the acceptable number of missing days and distribution. One way of determining if the gaps in a month are acceptable could be comparing the month with gaps with the complete months from other years. Then, if the incomplete month is within the range of dispersion for complete months from other years, the incomplete month is accepted. Otherwise it is rejected (9). Alternatively the monthly mean Solar Zenith Angle for measured data might be calculated for complete and incomplete months and the data accepted if the mean monthly Solar Zenith Angle is within of that for complete data set Another criterion could be developed taking into account the monthly mean solar zenith angle in full months and months with gaps.

Data Processing

- Capability of cosine error corrections.
- Capability of quantifying irradiance changes during a scan with a separate radiation sensor.
- Extrapolation of UV irradiance for wavelengths > 325 nm (for the calculation of erythemally weighted irradiance, and UV indices).
- Retrieval of total ozone column.

Instrument Characterization and Calibration

- All calibration information and procedures should be clearly documented and archived at the observation site.
- Weekly/monthly: Test of the stability of the spectroradiometer's spectral responsitivity, check of the wavelength alignment by correlation methods and/or by measurements of line spectra (e.g., with a low-pressure mercury lamp), determination of the spectroradiometer's bandwidth, checking levelling.
- Yearly (or as required): Calibration of working standards and reference standards (if necessary), measurement of the angular response of the spectroradiometer with respect to incidence and azimuth angle, characterization of linearity and offsets, stray light tests.

More details can be found in (1).

3.1.2 Broadband

Specifications Broadband B-1

Type B-1 instruments are defined as broadband instruments used for the measurement of erythemally weighted global irradiance.

Table III - Specifications broadband instruments type B-1 (2)

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

The table above should be considered in conjunction with Table I, according to the objective. For instruments within a network, it is recommended to use those with the least possible variability in their spectral response functions.

Ancillary Measurements

- 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).

Data Processing

- Capability to convert the instrument-weighted signal into CIE-weighted irradiance. This conversion is a complex function of environmental conditions (solar zenith angle, ozone column, clouds, aerosols etc.).
- Characterization of the spectral response.
- Capability of cosine error correction.

Instrument Characterization and Calibration

- 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 stability of the dark signal during the year. Instability may suggest temperature dependence of the electronics or other problems.
- 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.

More details can be found in (2).

3.2 Objective 2: To detect trends in global UV irradiance

Long term records (decades) are necessary for trend detection (10) . However, changes can occur on shorter timescales. For trend detection, instrument stability is crucially important.

For trends observed in most regions of the world, scanning spectroradiometers S-2 (1) are considered the most appropriate type suitable to accomplish this objective. The minimum requirements are as follows:

3.2.1 Spectral

Specifications Spectral S-2

Table IV - Specifications spectral instruments type S-2 (1)

Quantity	Quality
Cosine error§	(a) < ±5 % for incidence angles <60° (b) < ±5 % to integrated isotropic radiance
Minimum spectral range	290 - 400 nm+
Bandwidth (FWHM)	< 1 nm
Wavelength precision	< ±0.03 nm
Wavelength accuracy	< ±0.05 nm
Slit function	< 10^{-3} of maximum at 2.5·FWHM away from centre < 10^{-5} of maximum at 6.0·FWHM away from centre
Sampling wavelength interval	< 0.5·FWHM
Maximum irradiance	> 2 W m^{-2} nm^{-1} (noon maximum at 400 nm)
Detection threshold	< 10^{-6} W m^{-2} nm^{-1} (for SNR = 1 at 1 nm FWHM)
Stray light	< 10^{-6} W m^{-2} nm^{-1} (for SNR = 1 at 1 nm FWHM) when the instrument is exposed to the sun at minimum SZA
Instrument temperature	Monitored; typical temperature stability < ±2 °C to achieve a sufficient overall instrument stability
Scan time	< 10 minutes, e.g., for ease of comparison with models
Overall calibration uncertainty*	< ±5% (unless limited by threshold)
Scan date and time	Recorded with each spectrum so that timing is known to within 10 seconds at each wavelength

§ Smaller cosine errors would be desirable, and it is now possible to get input optics with very small cosine errors for those instruments for which a fibre optic input is usual. For details and definitions see WMO/Gaw Report 125.

* The overall calibration uncertainty includes all uncertainties associated with the irradiance calibration (for example: uncertainty of the standard lamps, transfer uncertainties, alignment errors during calibration, and drift of the instrument between calibrations).

+ For UV trend detection a smaller wavelength range e.g. 290-360 nm is likely to be sufficient, however, the larger wavelength range is required for many applications in biology, since biological weighting functions often include wavelengths higher than 360 nm (see page 5-7).

Ancillary Measurements

a) Required

- Independent measurements of global irradiance insensitive to ozone absorption, e.g., measurements of short-wave global irradiance with a pyranometer.
- Total ozone column, e.g., derived from direct normal spectral irradiance measurements
- Erythemally weighted irradiance, measured with a broadband radiometer.

b) Desirable

- Aerosol optical depth, e.g., derived from direct normal spectral irradiance measurements.
- Atmospheric pressure.
- Profiles of ozone.
- Profiles of aerosols, e.g., derived from lidar or backscattersondes.
- Profiles of temperature, air pressure and relative humidity
- Trace gases (relevant for NDACC and other tropospheric measurements).
- Clouds information (amount, type and height).
- Cloud images.
- Illuminance, measured with a luxmeter.
- Albedo.

Data Frequency

The measurement schedule of type S-2 instruments should comprise sufficient scans to enable an accurate (±10% uncertainty) daily integral of global spectral irradiance (i.e., daily global spectral irradiation) for days with no rain. If the spectra are sampled at fixed times, sufficient scans are needed to enable interpolation to fixed SZA for cloudless sky. Scans at local solar noon should be included.

Completeness

(See 3.1)

Data Processing

- Capability of cosine error corrections.
- Capability of quantifying irradiance changes during a scan with a separate UV sensor.
- Retrieval of total ozone column from global spectral data.

Instrument Characterization and Calibration

- All calibration information and procedures should be clearly documented and archived at the observation site.
- Weekly/monthly: Test of the stability of the spectroradiometer's spectral responsitivity, Check of the wavelength alignment by correlation methods and/or by measurements of line spectra (e.g., with a low-pressure mercury lamp), Determination of the spectroradiometer's bandwidth, check. Yearly (or as required): Calibration of working standards and reference standards (if necessary), Measurement of the angular response of the spectroradiometer with respect to incidence and azimuth angle including dependence on polarization, preferably in its, upright position,

Characterization of linearity and offsets, stray light tests.

More details can be found in (1).

3.3 Objective 3: To provide datasets for specific process studies (e.g.: atmospheric, biological and material sciences)

3.3.1 Scanning Spectroradiometer

As is the case of trend detection (objective 2), spectral instruments S-2 (1) are the most appropriate type of instrument suitable to accomplish this objective. Hence, the minimum requirements are as listed in 3.2.1., but completeness is not an issue. If the data are available they may be used, and are often gathered specifically for a particular investigation.

3.4 Objective 4: To validate radiative transfer models and/or satellite derived UV irradiance at the Earth's surface

The requirements are as listed in 3.3.

3.5 Objective 5: To understand geographic differences in global UV irradiance

The requirements are as listed in 3.1.

3.6 Objective 6: To gain information about actual UV levels and their diurnal and seasonal variability

The requirements are as listed in 3.1.

3.7 Objective 7: To provide data for public information and awareness (UV Index)

The requirements are as listed in 3.1.

If data are available in near real time they may be used for immediate public information (nowcast).

3.8 Objective 8: To supplement spectral UV measurements (e.g. temporal and spatial interpolation, interpretation of cloud effects

The minimum requirements are as listed in 3.1.2.

Completeness is desirable, but any available data may be used for the period when they were gathered.

3.9 Objective 9: To help in quality control of spectral UV measurements

The minimum requirements are as listed in 3.1.2.

Completeness is desirable, but any available data may be used for the period when they were gathered.

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