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

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

***Lead Author:* Ann R.Webb**

***Co-authors:* B.G. Gardiner, K. Leszczynski, V. Mohnen, P. Johnston, N. Harrison, D. Bigelow**

***Contributors:* S. Thiel, J. Metzdorf, J. Slusser, P. Disterhoff, T. Martin, E. Hare**

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PREFACE

The WMO Executive Council, through actions initiated by the EC Panel of Experts/CAS Working Group on Environmental Pollution and Atmospheric Chemistry (presently WMO/CAS Working Group on Environmental Pollution and Atmospheric Chemistry), has placed high priority on improving the quality and availability of the Global Atmosphere Watch (GAW) measurements. In order to address these needs and requirements for ultraviolet (UV) radiation, the WMO/GAW Scientific Advisory Group (SAG) for UV was established to develop and implement the monitoring programme for UV radiation in GAW. This includes proposing standards for compatible observations, quality assurance and quality control of measurements, data archiving, and connecting measurements with the user communities. The UV Monitoring and Assessment Program Panel (UMAP) co-sponsored the activities of the SAG UV and this is gratefully acknowledged.

The members of the WMO/GAW SAG UV at the time of writing this report are:

P. Simon (chair)	IASB-BIRA	Belgium
A. Kricker	USYD	Australia
S. Madronich	NCAR	USA
G. Seckmeyer	IFU	Germany
M. Shitamichi	JMA	Japan
P. Taalas	FMI	Finland
D. Wardle	MSC	Canada
B. Weatherhead	NOAA	USA
A. Webb	UMIST	United Kingdom
L. Jalkanen	WMO	Switzerland

This report, Quality Assurance in monitoring solar ultraviolet radiation: the state of the art, has been written in order to provide quality assurance strategies for the UV community. The report's main goal is to assist in harmonizing UV measurements. It has been extensively discussed and reviewed by the SAG UV and its subgroup on Quality Control. If some establishment has been left out from the lists of institutes offering UV calibration services, it has been unintentional. The report must be considered a working document that will be updated and revised according to new scientific and technological developments. Further comments and suggestions for this report are welcome.

Companion reports include the GAW reports "Guidelines for Site Quality Control of UV Monitoring" (No 126), "Instruments to Measure Solar Ultraviolet Radiation, Part 1: Spectral Instruments" (No 125) and "Instruments to Measure Solar Ultraviolet Radiation, Part 2: Broadband instruments measuring erythemally weighted solar irradiance" (in preparation).

The WMO acknowledges the great effort that has been put into this report, especially by the lead author Ann Webb.

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1. CONTEXT WITHIN GAW

The depletion of the stratospheric ozone layer and the resulting changes in UV radiation at the earth's surface reflect the increasing influence of human activity on the global atmosphere, the life-support system of planet earth. The rationale for the WMO Global Atmospheric Watch (GAW) programme is driven by the need to

- understand the complex mechanisms of natural and anthropogenic atmospheric change
- improve the understanding of interactions between atmosphere, ocean and biosphere
- provide reliable scientific data and information for national and international policy makers.

The future development of the UV measurement parameters has been specified by the Scientific Advisory Group on UV radiation (SAG UV). With UV radiation linked to several harmful effects on many forms of life, either directly (biological damage) or indirectly (quality of life) and with its influence on fundamental chemical processes in the atmosphere, the necessity for monitoring surface UV radiation and quantifying future changes is of great importance. Monitoring UV radiation together with other factors such as ozone, aerosols and cloud cover allows UV radiation conditions to be defined on regional and worldwide scales, as well as determining, quantitatively, the factors that effect the surface UV dose.

Besides measurement activities, modelling of the radiative transfer of UV radiation has become important. Radiative transfer models have been applied in the development of satellite-based methodologies for estimating the UV-irradiance on the earth's surface. UV monitoring from space offers the opportunity to achieve global coverage of the UV radiation field: effective monitoring of our planet on a global scale will require the integration of satellite derived observations with ground-based measurements. The information derived from such an Integrated Global Observing System (IGOS) is only useful to policy makers if the underlying data are rigorously quality assured, i.e. are "of known quality and adequate for their intended use". Consequently the design and implementation of a comprehensive quality assurance plan for the UV component of GAW is an integral part of the entire GAW programme (see Annex 1).

Quality assurance in GAW consists of three elements:

- Definition of Data Quality Objectives (DQOs). This process is led by the SAG UV and is a prerequisite for preparing the quality assurance plan including the standard operating procedures (SOPs). The DQOs are derived from the "intended use of the data" and also reflect the technological constraints – if any.
- Quality Control. This activity is the responsibility of the data producer and requires adherence to "good laboratory practice" as well as all measures that directly or indirectly influence data quality. The data producer is held responsible for following the SOPs. The data producer is the primary guardian of the data quality.
- Quality Assessment. This activity is an "external" review of data quality by a group/organization which is independent of the data producer. It ensures that all quality related measures have indeed been carried out by the data producer. Upon careful review and audits, the quality of data is certified.

This document reviews the current "state of the art" in UV measurements and associated quality assurance activities worldwide and forms the basis for the development of a comprehensive GAW – UV quality assurance plan taking into account the – though be it fragmented – facilities and services already existing around the globe. Furthermore, this document emphasizes the need to adhere to "traceability to the SI system of units for Earth Observation (EO) measurements". This will ensure comparability of data and compatibility of measurements obtained from all global observing systems, including satellite observations. Quality assurance is an evolving process and requires periodic upgrading to take advantage of technological advances.

2. THE PHILOSOPHY OF QA IN SOLAR ULTRAVIOLET MONITORING

2.1 Introduction

The following remarks were written with spectroradiometers in mind, but they can be applied also to broadband and multichannel radiometers in general.

The aim of Quality Assurance is to convince the user that a certain level of quality has demonstrably been achieved. In the case of ultraviolet spectroradiometry, this can be done by two methods, which may be loosely referred to as the deductive and inductive, or forward and reverse, methods.

In the first method, the user is presented with a detailed and comprehensive description of the calibration and related procedures, together with the results of their regular application, and all the appropriate determinations of instrumental characteristics such as slit and cosine functions. The user is persuaded that these procedures have been carried out diligently, or at least adequately, or perhaps roughly, and can then judge the general level of accuracy (see Annex 2) that has probably been achieved. From that the user *deduces* the quality of the individual measurements which are to be used.

In the second method, the instrument is compared with a number of other instruments, and the quality of its results is judged according to how well it agrees with the others. We may regard this method as *inductive* , since it seeks to infer the general level of performance from the particular behaviour encountered during the intercomparison.

Each method has its advantages and its disadvantages. Let us examine them.

2.2 Methods

The deductive (first) method, if done well, would be ideal: it could be carried out at the home site, as a routine set of procedures, and defend itself by demonstrable repeatability during regular series of cross-checked calibrations. f the operator could provide enough experimental support for the calibration analysis, clearly expressed, the user might become convinced that the quality was satisfactory in respect of all the measurements covered, and could extend the analysis to the subsequent data products. Unfortunately, in practice, this seldom happens. The detailed calibration results are not generally available, the procedures are usually internal to the operator's institute, and there is little or no information on the methods used to guarantee that all significant sources of error have been fully taken into account. In any case, there is seldom any quantitative analysis of the quality of the measurements.

The main advantage of the inductive (second) method (instrument intercomparison) is that the results are independent of the calibration analyses performed by the operators. In principle, the intercomparison method also ensures that all sources of error are automatically included, but it suffers from the drawback that it tends to mask any error that is common to the various instruments. For example, if several instruments have a similar erroneous cosine response, the intercomparison method may give a false assessment of the measurement accuracy. Furthermore, the independence and consequent objectivity of the intercomparison method can only be obtained if a blindness protocol is enforced, so that the instruments perform independently of each other. Even then, the results are strictly relevant only during the intercomparison itself: their extension to the measurements made later at the home site is quite problematical. This is possibly the most intractable aspect of the inductive method.

As neither method is perfect, we need to make use of both. In order to combine them, their assessments of quality must be expressed in some common currency. It is notoriously difficult to assign quality flags to measurements of this sort, as they are invariably open to the charge of arbitrariness, even if the procedures are laid down objectively. The most scientific approach is to express the quality in terms of uncertainty estimates, and to defend them by explaining and documenting the estimation procedures. It is then possible in principle to compare the uncertainty estimates obtained by the two methods outlined above, and to reconcile them as required.

2.3 Objectivity and uniqueness

The reader should be under no illusion that objectivity can easily be achieved when assessing uncertainties. Most uncertainty estimates are inherently subjective, and this is especially true in spectroradiometry, where statistical estimates are seldom available, and then only for some components of uncertainty. Nevertheless, quality assurance is about engendering confidence, so the uncertainty estimates must be credible. They should therefore be either transparently objective, or openly subjective but well argued and fully explained. Wherever possible, the implementation of the estimation procedures should be objective even if their design is not.

We have seen that there is more than one way to arrive at an assessment of quality on the basis of estimates of uncertainty. It follows that the resulting estimates are not unique. They depend not only on the sources of information (operators' calibrations, international or local intercomparisons, manufacturers' certificates or generic specifications, performance of similar instruments and components, physical calculations, observational experience, etc.), but also on the level of care that is taken over the process of estimation, the exact approach in specifying and implementing the estimation method, and the skill and judgement of the estimator. Moreover, the same estimator may produce more than one version of an estimate. For example, an estimate may be improved on the basis of new evidence, fresh calibrations, or a more detailed or critical analysis of existing data.

Quality assessments may also be designed for different purposes. Safety-critical operations may require a more stringent level of quality assurance than general-purpose scientific research applications, which in turn may be more exacting than mere guidance to assist a user in deciding which instruments or data sets might suit his purpose. This will have an effect on the approach used in the uncertainty estimation.

2.4 Implementation

The two methods which are available to us in ultraviolet spectroradiometry, outlined above, in section 2.2, must be implemented according to rather distinct criteria, if they are to serve the needs of uncertainty estimation.

The deductive (first) method, which depends chiefly on calibrations carried out by the instrument operator at the home site, requires exhaustive documentation and transparency, possibly including independent evaluation and certification: this option is currently out of reach in most cases, as the user has little or no access to such information.

The inductive (second) method, which is based on intercomparison, is also strengthened by good documentation, transparency, and independent evaluation, but its principal requirements are blindness, objective comparison algorithms, and sound interpretation regarding the generality, independence, stability, and reliability of the results. In practice, this is the only technique available at present for providing quality assurance to the general user. It is not currently implemented in terms of uncertainty estimates, but it offers the most promising vehicle for an early realization of the uncertainty-based approach. If a satisfactory numerical assessment of quality cannot be obtained from an intercomparison, where the evidence is visible to all, and the analysis follows an objective procedure which the participants can repeat for themselves, then it will certainly not emerge from laboratory calibrations at the home sites, where the evidence is not readily available to the subsequent data user and the experiments cannot be repeated by others. Nevertheless, information from both methods is necessary in order to arrive at a reliable level of quality assurance.

The way forward is therefore to develop protocols for estimating, combining, and documenting components of uncertainty for each individual measurement and data product, based on the above methods. The protocols must be of general applicability, which means that they should work even when there is little or no information available: it must be possible to apply the protocols successfully even when the potential sources of uncertainty in a measurement have not all been fully characterized. The only proviso is that the basis of the assessment should be adequately documented, whether it is modest or comprehensive. In that way, an operator could provide a well-documented uncertainty estimate from the outset, and subsequently refine it by incorporating more detailed evidence.

2.5 Procedures

The detailed procedure for the deductive method, which depends on forward calculations based on the results of laboratory calibrations and experiments, should follow the principles laid down in WMO/GAW Report No. 126 (1), which outlines a method for arriving at a general estimate of uncertainty, applicable to an instrument at an observing station. For quality assurance purposes, the estimation should be supported by documented evidence, presented according to an accepted standard form, including traceability, and the results should be expanded to reflect the variations in uncertainty which depend on the passage of time, and on wavelength, solar zenith angle, and observing conditions. For example, the uncertainty estimates will be greater during periods in which the lamp calibrations were disappointingly inconsistent. The aim is that the user should be able to arrive at a reliable and convincing uncertainty estimate for any of the measurements and derived products. A comprehensive attempt at a rigorous uncertainty estimate is given in Bernhard and Seckmeyer, 1999.

The most problematic elements of the above deductive procedure are the provision of convincing evidence of calibration accuracy and stability, elimination of stray light, reliability of the cosine response and its subsequent correction, if any, and freedom from computational errors in the chain leading from raw data to final result. By contrast, the most difficult areas in the inductive method revolve around questions of clustering and common effects. The quality of the measurements in an intercomparison can only be judged by the extent to which the various instruments agree with each other, but the agreement may result in part from their sharing a source of error, such as an erroneous cosine response or a common irradiance standard, which has either passed unnoticed or received an inadequate correction. A realistic assessment of uncertainties based on intercomparison results must allow for these effects either by accounting for them directly or by incorporating relevant information from elsewhere.

There have been many intercomparison campaigns, at various levels of complexity and sophistication. A selection of typical cases is given below (refs. 2 to 15). Most campaigns are analysed with respect to an arbitrary norm such as the host instrument or the mean of all the instruments present. However, recent European campaigns (9, 13) have attempted to improve on this system by introducing more objective and dependable algorithms for the analysis of the results. The main aim is to establish a transparently objective central norm which can serve as a reference for comparison purposes. The norm is weighted towards the median, and the reference algorithm attempts to reflect the tendency of the various instruments to agree in their measured results, and the stability of that agreement with respect to time and wavelength. Objective procedures have also been developed to select a self-consistent set of instruments and simultaneous observations from those available at the intercomparison, from which the central norm can be calculated, taking into account the distribution of suitable observations as a function of solar zenith angle and time of day.

The outcome of the inductive procedures and algorithms is a credible numerical assessment of the quality of the instrumental results, at least as far as it can be inferred from the measurements carried out and reported during the campaign. From the point of view of quality assurance, this should provide a more convincing and reliable evaluation than can be obtained from a more simplistic or subjective analysis, but all such evaluations suffer from the inherent deficiencies of intercomparisons, namely that the most consistent instruments may share correlated systematic errors, and that the performance of the instruments at the intercomparison does not necessarily reflect their behaviour at the home sites.

2.6 Requirement

Given that quality assurance can be based on evidence from both of the methods described above, the requirement for progress in this field is now clear. It is necessary to lay out a detailed procedure for the provision and documentation of uncertainty estimates by each method, taking into account variations with respect to wavelength, solar zenith angle, and observing conditions, as well as operational variables in the instrumental procedure. For the forward method, guidelines for the estimation of uncertainty components will be found in WMO/GAW Report No. 126 (1), which contains technical details of the various sources of uncertainty, together with directions concerning their estimation and combination. However, the general algorithms in that report will have to be refined and applied to the full range of measurements, so that an uncertainty estimate is available for each individual measurement, not merely for a typical measurement at the station.

In the case of the reverse method, which is based on the results of intercomparisons, the analysis must take into account estimates of the uncertainty due to factors not tested in the campaign, as well as the observed variations between the instruments, and should also consider any effect on the results due to local recalibration at the campaign site before participation in the campaign.

In both methods of assessment, default estimates should be provided for any sources of error which lack observational or experimental evidence. In the forward method this will include aspects of consistency and repeatability which have not been checked, while in the reverse method it will cover questions relating to the presence or absence of intercomparison tests over a period of time, the availability of campaign assessments, and the relationship between these results and the operational regime at the home site. In this respect a practical method of linking the two approaches would be to use a travelling standard instrument, providing for an intercomparison at the home site. To gain credence this method requires wide acceptance of the travelling standard as a reference of higher order than the site instruments, and exceptionally high standards of maintenance of the travelling instrument, including a dedicated operator. The same types of protocols are needed as for the large intercomparisons, including the blindness criterion, but without the need to define a reference, which is now taken as the visiting standard instrument.

Finally, the information gained from the different methods should be incorporated into one estimate, which will provide an assessment of data quality for the user, and thereby offer some level of quality assurance in respect of the measurements themselves and any data products derived from them.

The procedures described above depend largely on evidence based on experimentation: it is an interesting question whether model results could eventually play a convincing role in quality assurance. Provided it was clearly described in the documentation of the uncertainty estimation, this would certainly add another dimension to the quality assurance process. It seems likely that this will become more plausible once a body of reliable quality assessment evidence has been accumulated on the basis of laboratory calibrations and intercomparisons. Modelling could then provide evidence regarding relative variations between different instruments and measurement conditions, which would broaden the scope of the experimental assessments. Some consideration should be given to the necessary procedures for this aspect of quality assurance at an early stage, so that it can be properly incorporated in due course.

Throughout the development of methods of assessment for quality assurance, provision should be allowed for successive improvements in the specification and implementation, so that the complexity of the task does not preclude early and useful estimates based on summary and approximate considerations and information. However, the procedures should be drafted in such a way as to encourage a more diligent approach: in general, lack of attention to detail, and lack of evidence in particular aspects, lead to larger uncertainties, and therefore to more pessimistic estimates and assessments.

As a long-term aim, data formats and software should be developed to allow the inclusion of uncertainty estimates in databases, so that the processes leading to quality assurance become routine, accepted, well documented, and widely available and understood by both the occasional and the regular user of the data. As ultraviolet spectroradiometry is a particularly awkward case to deal with, there is some prospect that success in this field might also provide tools for others to use, particularly in other geophysical and environmental applications.

3. GLOBAL OVERVIEW OF QA PRACTICES

The WMO has established several World Calibration Centres (WCC) for parameters that are measured in the GAW programme. There is a WCC for solar radiation measurements at the Physikalisch-Meteorologisches Observatorium Davos/World Radiation Centre (PMOD/WRC) in Davos, Switzerland. Although on the agenda of the SAG UV a global calibration facility for UV radiation measurements has not been established. However, there are two regional centres (see below section 3.1.) which may prove to be a more feasible approach as long as the regional efforts are connected to one another.

Even in general terms, there are currently no globally acknowledged QA services undertaking QA for the UV monitoring community. Instead there is a disparate collection of services offered by regional centres, manufacturers and individuals that offer a first step towards improving QA. Most of the services are some form of calibration and/or instrument characterization. They are not QA facilities in the strict sense since they do not generally provide ISO 9000 certification, auditing, QC analysis, or even comprehensive instrument testing. Nor is there any external check on the calibration services, other than the performance of serviced instruments in subsequent intercomparisons.

Although the provision of practical means for assessing quality of UV measurements is poor, there are similar statements from several sources on the performance required from instruments. These usually concentrate first on spectral instruments, and since the calibration of the more numerous broadband radiometers must revert in the end to a spectroradiometer, this is a good place from which to start the consideration of QA needs. Several international bodies have recommended requirements for solar UV measuring systems, based on the prospective uses of the instruments. WMO has recently published “Instruments for Measuring Solar Ultraviolet Radiation Part 1:Spectral Instruments” (16a) and Part 2 on broadband instruments is being published (16b), while the relevant parts of a statement from CEOS-IGOS declares:

> Accurate knowledge of the solar ultraviolet radiation, which drives atmospheric photochemistry and provides the photons that ultimately reach the Earth's surface, is essential if quantitative knowledge of the relationship between atmospheric ozone levels and surface ultraviolet radiative fluxes is to be obtained. The wavelength range that covers the links between atmospheric chemistry, surface ultraviolet radiation and UV effects extends from approximately 280 to 400 nm. Wavelength resolution of at least 1 nm is required, especially in the UV-B region, where the absorption cross section of ozone exhibits significant wavelength dependence that will have a major impact on the surface flux of ultraviolet radiation.

The data quality objectives (DQOs) for measuring *spectrally resolved shortwave (UV)* solar irradiance are primarily derived from the following GAW programme goals:

- To understand the spectral consequence in the UV region of changing atmospheric composition (e.g., ozone, aerosols, clouds)
- To understand geographic differences in global spectral UV irradiance
- To establish a UV climatology by long-term monitoring, e.g. within a network of UV spectroradiometers
- To detect trends, especially spectrally resolved tends, in global UV irradiance
- To provide datasets for specific process studies and for the validation of radiative transfer models and/or satellite derived UV irradiance at the Earth’s surface
- To gain information about actual UV levels
- To monitor long term changes in UV irradiance

- To make properly calibrated UV data available to the community

The quantities measured are primarily global spectral irradiance in the UV and direct (normal or horizontal) spectral irradiance in the UV, and the measurements are generally made in conjunction with other corroborative measurements to support the analysis.

Instruments satisfying all the above purposes are generally not yet commercially available and represent the state-of-the-art in ongoing research and development (see Instruments for Measuring Solar Ultraviolet Radiation Parts 1 and 2 (16a and b) for more information).

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. The primary interest is in UV increases resulting from reductions in total ozone column. However, in this context, possible reductions in UV resulting from future recovery of the ozone layer, or from a build up of tropospheric pollution (e.g., aerosols, ozone) or stratospheric particle loading may be relevant as well.

Such DQOs for UV measurements are generally based on the need for trend detection (in mid-latitudes, these trends are expected to be less than 10% per decade) and on studies of biological organisms. The total measurement uncertainty of modern instruments used for spectrally resolved trend detection should therefore be considerably smaller than 10%, leading to stringent limits on the many aspects of the instrument performance that can lead to uncertainty (Instrument document). The instruments must also, of necessity, be proven stable for many years of operation and so need regular assessment through appropriate QA/QC measures. Thus, the stated aims of the great majority of UV measurement programmes would be well served by an acknowledged QA procedure, and QA facilities.

Due to the obvious instrumental differences, the objectives for *broadband measurements* are different. The main objectives are:

- To provide information on short-term (from a few seconds up to a few months) variations of erythemal irradiance
- To allow the determination of a UV index or to provide data for public information and awareness
- 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 understand geographic differences in erythemally weighted global UV irradiance
- To evaluate UV retrievals based on satellite measurements.

The quantity measured is primarily global spectral irradiance in the UV weighted by the spectral responsivity function of the radiometer (usually erythemally weighted as stated above, although other weightings may be used).

At a fundamental level some QA does exist for the sources that are the basis of all absolute calibrations, the standards of spectral irradiance used with spectroradiometers. These are subject to the QA of the National Metrology Institutes (NMIs).

National Metrology Institutes are responsible for establishing primary scales for UV spectral irradiance and enabling access to those scales to the user community. These scales are defined in terms of well-characterised SI units so that they are reliable in the long term, are comparable world-wide and are linked to other areas of science and technology through the world's measurement system established and maintained under the Convention du Metrè. Spectral irradiance scales are usually maintained on a source such as a high temperature black body. The primary standard source is then used to calibrate secondary standards, usually tungsten halogen lamps which are in turn used to calibrate working standard lamps. These working standards are then used to calibrate customers' lamps. NMIs have well documented procedures used for establishing spectral irradiance scales and for the calibration of customers' lamps. NMIs generally have or are moving towards implementing formal quality systems which are independently audited. Similarly, calibration services offered by NMIs are sometimes accredited by an independent measurement accreditation service such as the United Kingdom Accreditation Service (UKAS) in the UK. The scales established by NMIs are intercompared at regular intervals in blind intercomparisons organised under the auspices of the Consultative Committee for Photometry and Radiometry (CCPR). The most recently published CCPR intercomparison took place in 1991. At the time of writing a CCPR Key Comparison of spectral irradiance is underway. NPL is acting as pilot laboratory with participation from NMIs around the world who have a proven historical record of research in this area. This key comparison is expected to be completed by the end of 2003. There will also be a comparison of air-UV spectral irradiance piloted by PTB using deuterium lamps for the spectral range 200 nm to 400 nm starting in 2003.

In October 1999 the directors of the national metrology institutes (NMIs) of 38 states which are signatories of the convention of the metre, agreed to the Mutual Recognition Arrangement (MRA). Under this arrangement calibration certificates and measurements made in one country would be automatically accepted in another, without the need for individual bilateral agreements. MRA operates through comparisons organised by the working committees of the Comite International des Poids et Mesures (CIPM). The most important of these are the so called "Key Comparisons" of the most basic quantities associated with each SI base unit. The Key Comparison of spectral irradiance is a typical example. The results of these Key Comparisons establish a Reference Value for each quantity, which is an approximation of the true SI quantity. This is followed by a series of regional comparisons of the same quantity to bring all the other NMIs into the system. The results of all the comparisons, together with the differences of each laboratory from the reference value, are then entered on to a database accessible via the internet at the BIPM web site (www.bipm.fr).

Historically UV spectral irradiance scales disseminated from NMIs have suffered from uncertainty levels of several per cent, especially at the shorter wavelength end of the scale. When intercomparisons have taken place there has been a wide distribution of results. In the last CCPR intercomparison the results at 300 nm show a spread of ±5%. Subsequent bilateral and indirect intercomparisons have shown changing levels of agreement between NMIs. Typically the agreement between different NMIs has remained within the combined uncertainties of the scales. A number of NMIs are in the process of re-establishing their spectral irradiance scales by linking them to primary detector scales. The uncertainty level (1 sigma) of these new scales on primary standards is of the order of a few tenths of a per cent in the UV, varying with wavelength. However, the performance of transfer standard lamps in this region is poor and can be identified as a key component of the disappointing level of agreement between NMIs in intercomparisons and the change in the level of agreement in different intercomparisons.

The FEL tungsten halogen lamp is currently the predominant spectral irradiance transfer standard used for disseminating UV spectral irradiance scales from National Measurement Institutes to the end user. Recent work (17, 18) has raised concerns about the FEL lamp's usable lifetime and performance after transportation. Changes in the spectral irradiance of the lamp of up to 1.5% (varying with wavelength) have been observed. The effects of transportation may also explain why FEL lamps from the same NMI may differ by more than their stated uncertainties as reported in (19). Tungsten halogen lamps used as transfer standards are typically lamps that have been designed for other uses such as projector lamps. They have not been optimised for use as spectral irradiance standards. Typically, these lamps have a filament that consists of single or double-coiled tungsten wire suspended between two vertical or horizontal filament supports. During the heating and cooling stages of lamp use the filament has to withstand significant thermal and mechanical stress that can cause the filament to change conformation producing a sudden change in output. Transportation also subjects the filament to substantial mechanical shocks, which can result in similar shifts in spectral irradiance. In addition, during the operation of the lamp tungsten is preferentially deposited on certain places on the filament causing growth of tungsten tendrils that can short out coils that are closely packed. This effect also results in a sudden change in the electrical properties of the lamp. A promising development is the active stabilising of the spectral irradiance from a lamp by detector feedback (18, 20a, 20b). This involves linking cheap, robust and stable detector technology to an irradiance standard lamp, such that the lamp current is adjusted to maintain a constant signal on a monitoring detector. When combined with an appropriate filter to define a spectral band and after initial solarisation and ageing effects have occurred, the output of the lamp over a defined spectral band can be maintained to better than 0.5% over 500 hours operation. Changes in the electrical characteristics of the lamp, ageing of the lamp envelope, changes in coil conformation, transportation effects etc., can all be compensated for by detector stabilisation. Detector stabilisation shows great promise for improving the dissemination and comparison of scales.

The absolute calibration of a (spectro)radiometer is only one aspect of the process of taking a reliable UV measurement. QA of the total measurement procedure (the resulting data) on a national or international scale has generally been restricted to the inductive method of intercomparison, with all its attendant drawbacks. Nonetheless the process has lead to great improvement in the quality of UV measurements and a better understanding of the factors that contribute to a good (or bad) measurement. The greatest efforts at standardization through intercomparisons have focussed on the spectral detectors. A series of international intercomparisons supported by the EC will be used to illustrate the evolving QA and the progress that has been made towards standardization in the past decade. Although these are not the only intercomparisons to be reported in the literature they do represent the longest running series and the most widespread international coverage.

The EC series of intercomparisons began in 1991 with 6 instruments at a site close to Thessaloniki in northern Greece. Further intercomparisons in 1992, 1993 and 1995 are reported in Gardiner and Kirsch (2,3,5,8) and Webb (21) respectively. The early intercomparisons served to illustrate the need to work towards better standardization, to show the aspects of measurement where reasonable agreement already existed, and the major sources of the remaining (significant) discrepancy in solar UVR measurements. The latter proved to be the basic standards of absolute irradiance (lamps, which must be accepted as a baseline uncertainty), the transfer of these standards to the instrument during calibration, and the instrumental features of wavelength alignment, slit function and cosine response.

The latest intercomparison: Standardisation of ultraviolet spectroradiometry in preparation of a European network (SUSPEN) in the series was held at Nea Michianona in northern Greece in July 1997, where a total of 19 spectroradiometers participated, including not only EC based systems but also instruments from New Zealand, Canada and USA (22). In addition to the four EC field intercomparisons and a laboratory campaign, similar exercises had been held elsewhere, for example in the United States (11,12) and amongst the Scandinavian countries (10). This experience showed that there has been a vast improvement in the understanding of the instrumental and operational requirements for reliable measurements, coupled with advances in data correction and analysis techniques that helped to overcome some of the practical problems of building the perfect instrument.

Figure 1 shows the ratios of all 19 spectroradiometers, from around the globe, present at the 1997 international intercomparison in Nea Michianona to the reference spectrum on one of the blind measurement days. In general, agreement at this and other intercomparisons is best when the solar zenith angle is small (close to solar noon), and at the longer UVB and UVA wavelengths, so performance over a range of solar zenith angles must be investigated to ensure that all daily and seasonal data from the instrument will be of the same standard. In the example given a large number of instruments have a spectrally flat ratio that falls within the boundaries of the uncertainties that might be attributed to differences in standards of absolute irradiance (typically ±5%). Inspection of all the results showed that 11 instruments were within 5% of the reference for

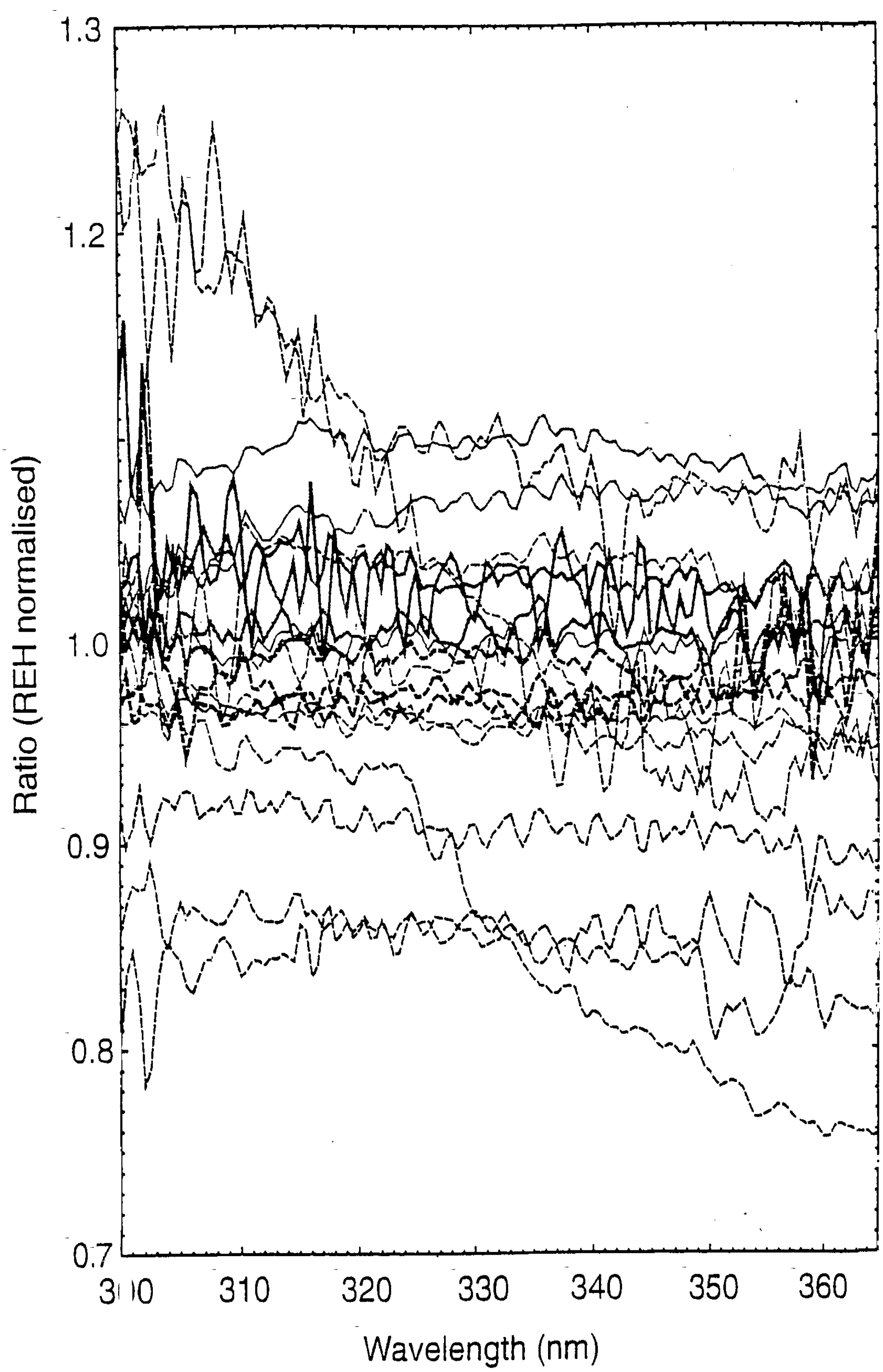

Figure 1: ***Average daily spectral UV measurement ratios for 19 instruments, each ratioed to the Intercomparison reference spectrum for Julian day 185. From the SUSPEN Intercomparison, Greece, 1997. Data have all been analysed using the SHICrivm procedure. Solid lines are instruments to which a cosine correction was applied. Dotted lines are instruments with no cosine correction. Thick lines represent those instruments that were used to determine the reference, selected using a pre-defined algorithm.***

the midday scan on both blind days, and across the full spectrum. Both the spectral and diurnal variations of the majority of the instruments did not exceed 5% compared to the reference. Overall, the authors of the SUSPEN report concluded that 12 instruments produced results of sufficient stability to give confidence that both instruments and operators would continue to perform well, though absolute irradiance calibrations still needed to be reconciled (22). It should be noted that this was a group of well characterized instruments run by experienced operators. Other instruments in the intercomparison did not perform as well. However, this is a great improvement on earlier results and indicates the value of such external QA, without which it can be extremely difficult to identify and remedy some of the inconsistencies that may arise in spectral measurements.

The simpler operation, more robust nature, and cheaper cost of broadband radiometers, compared to spectroradiometers, means that there are far more organized networks of broadband (predominantly erythemal) radiometers on a regional or national basis. Individual networks have their own QC and internal QA practices, but there have been few larger scale investigations of the performance of a wide range of such radiometers. The most comprehensive exercise to date was the World Meteorological Organization (WMO) intercomparison held at the Finnish Centre for Radiation and Nuclear Safety (STUK) in 1995 (14). A more recent intercomparison campaign was held at the Aristotelian University of Thessaloniki, Greece, in 1999, co-organized by COST 713, WMO, and the Laboratory of Atmospheric Physics (LAP-AUTH), (23). In connection with the intercomparison in Greece, a small-scale intercomparison supported by WMO was also arranged at STUK to compare the characterisation and calibration results between these two laboratories and to get some indicative information on the stability of the meters since the 1995 WMO/STUK intercomparison.

In both intercomparisons, in Finland and in Greece, all the broadband meters were designed to measure erythemally weighted solar radiation following the CIE erythemal action spectrum. Both the intercomparisons were performed by 1) characterising the radiometers by measuring their spectral and angular responses in the laboratory and 2) calibrating the radiometers in solar radiation against simultaneously measured CIE-weighted spectroradiometric UV data. In both intercomparisons, two well-characterised and calibrated spectroradiometers were used as reference instruments.

In Finland, 20 instruments from networks in 16 countries took part in the WMO/STUK 1995 intercomparison. They represented six different types (make and model) of radiometer. Significant variations were found in both spectral and angular responses, even though 16 of the meters came from the same manufacturer, clearly illustrating the differences between radiometers that are often assumed to be identical. Both the spectral and angular responses will cause increasing uncertainties of measured UV data as solar zenith angle increases if the calibration process follows the most common method of defining a single calibration factor as an average of calibrations at solar elevations higher than 35°. The calibrations performed at the WMO/STUK intercomparison were estimated to have an absolute uncertainty of ±10% under similar conditions to those of the calibrations: uncertainties increase under different atmospheric conditions. The original independent operator calibrations showed far greater diversion than this (14, 24).

An alternative method to achieve better homogeneity of data from different instruments, is to calibrate (against a spectroradiometer) using the actual response spectrum of each meter, and then to calculate a transfer from meter-response units to erythemal response units. The transfer depends on solar zenith angle and ozone amount (determining the spectrum of incident radiation) and requires a radiative transfer model, run under the whole range of conditions likely to be encountered at the measurement site (25).

In the intercomparison in Greece, 29 instruments (seven different types) from 14 countries took part in the campaign. Besides calibrating against the CIE-weighted irradiance, the radiometers were also calibrated against the spectral measurements weighted with the actual spectral response of each radiometer. For several instruments the newly determined calibration factors did not differ more than a few percent from the ones provided by their manufacturer, but other instruments showed deviations exceeding ±20% between the intercomparison and manufacturers' calibrations. The sensitivity of an instrument is expected to decrease with time, and therefore the calibration factors should also decrease. An increase in the calibration factor can be produced by a shift in its spectral response towards longer wavelengths. The large deviations of the new calibration factors from the ones in use point to the necessity for more frequent checks of the calibration of these instruments. Details of the measurement and data analysis procedures and results for all instruments can be found in (23).

The results from the 1999 small-scale intercomparison of two meters at STUK agreed with the results obtained in 1995 within the estimated uncertainties. However, the calibration of one of the meters indicated a change of the sensitivity by several percent. Hence, to confirm the stability of broadband meters, frequent recalibrations are necessary, preferably on an annual basis. Also, the 1999 results obtained in Greece and Finland using different characterization methods and at different calibration locations, agreed within measurement uncertainties.

The level of agreement between independently operated broadband radiometers can clearly be improved. Two approaches would lead to improvements in the current situation. One is to have a central calibration facility: as the calibration process begins with a spectroradiometer as the standard for comparison, the agreement between radiometers can only be worse than the agreement between the spectroradiometers used as the standards, since the calibration process itself introduces additional uncertainties. Once a well characterized radiometer has been centrally calibrated it may then be used to calibrate other network radiometers with similar characteristics *in situ* with comparative ease, since the radiometers are robust and easy to transport. Such an exercise can also indicate whether there has been a change in characteristics or calibration of the network radiometer since a previous comparison. In this way improvements in the standardization of erythemal UV radiation would become widespread. The service of such a "standard instrument" is currently offered by some manufacturers for their own instruments, and used within some regional and national networks. However, there is no link between, or QA of, the various "standards" for the different networks. The second method is to adopt the two stage calibration process based on the actual response spectrum of each instrument, then convert this to erythemal units. However, this requires the facilities to measure the spectral response of each meter, and to check it at suitable intervals as response can change as the instrument ages. Such facilities could once again be provided centrally as characterization is not a frequent requirement.

3.1 Central Initiatives

The importance of well supported central facilities in implementing transparent QA practices is clear in principle, but less easy to achieve in practice. The centre must have significant financial support and must establish its right to pass judgement on the performance of other data producers by proving the consistency and widely accepted "rightness" of its own procedures and measurements. At present there are two different approaches to a central facility being established, one in North America and the other in Europe.

The North American approach has been to build a state of the art laboratory and field site facility to which instruments can be brought, or sent, for a wide range of calibration and characterization services. The Central UV Calibration Facility (CUCF) was developed from a plan originated by the United States Global Change Research Program (USGCRP). The USGCRP panel is comprised of delegates from many US government agencies. Several of the agencies are involved with the UV-B monitoring effort in the United States and polar regions. Each agency realized that they would have a need for a calibration facility. On consultation from the National Institute of Standards and Technology (NIST) it was agreed by the other agencies that one central facility would be developed as a joint NIST and NOAA project. This was agreed upon in an effort to minimize biases introduced by each individual agency having its own calibration facility. It was also understood that by developing one central facility the costs could be diluted among the participating agencies, instead of each agency suffering the financial burden of supporting its own facility. This facility has later become the WMO/GAW Regional Calibration Centre for UV for North America.

The CUCF, located at the NOAA David Skaggs Research Center in Boulder, CO, has been in full operation since 1997. It is comprised of three components; the central laboratory, the field test facility, which is 8 miles north of Boulder, and the high altitude observatory. Each of these components serves a special purpose to help facilitate the CUCF in completing its mission.

The central laboratory is mainly used for the testing and calibration of working standards of irradiance, the calibration and characterization of broadband and narrow-band radiometers and the characterization of spectroradiometers. The portable field calibration system (26), developed by NIST and CUCF scientists, is utilized for the calibration of spectroradiometers at field sites of the US networks. The laboratory has developed dedicated characterization systems for the measurement of the spectral response, the angular response and absolute response of UV radiometers. For spectroradiometers, the laboratory is capable of measuring their slit-scattering functions, the stray light rejection, and their wavelength calibration. In conjunction with NIST, the CUCF has also developed a dedicated system for transferring the NIST irradiance scale from primary standards of irradiance to secondary or working standards. This system can accommodate FEL-type lamps operating with the long axis of the filament either horizontal or vertical. The reason for this is that most radiometers are calibrated in an upward viewing mode while standard lamps are calibrated by NIST with the filament axis vertical. As a consequence, the horizontal irradiance can be different by 6-8% from the vertical irradiance of a FEL-type lamp.

The CUCF's reference spectroradiometer (supplied by the USDA) and reference broadband radiometers are permanently located at the field test facility. In addition to broadband calibrations (27) and field testing, the site also serves to host UV monitoring instrument intercomparisons (11,12, 28) and long-term UV monitoring.

The high altitude observatory is currently used as a long-term UV monitoring site, but can also be used to calibrate instruments via the Langley method.

In Europe a new initiative has begun with the support of the European Commission. A travelling standard spectroradiometer is to be established, with its own mobile support laboratory and dedicated operator. The instrument will be available to travel to monitoring sites within Europe to perform *in situ* intercomparisons and calibrations of the site instrument, and check some of the site instrument characteristics and calibration facilities. The travelling instrument will be supported by a fully equipped laboratory and data analysis service at the EC Joint Research Centre (JRC), Ispra. The credentials of the instrument will be established through intercomparison with a suite of the longer established spectroradiometer groups in Europe (2002) followed by series of test visits first to the sites of the intercomparison spectroradiometers, and then to a wider range of sites and instruments (2003 and 2004). The implementation and testing of the facility is expected to take 3 years, after which it will be put into full operational service, operated by JRC and in cooperation with WMO. Other facilities emanating from EC funded research provide for the calibration of ultraviolet dosimeters, but could also be used to the same purpose with radiometers (29).

In addition to the above, a WMO/GAW Regional Calibration Centre is being established in Buenos Aires, Argentina, by the Servicio Meteorologico Nacional. They will host their second intercalibration exercise for broadband instruments in November 2003.

4. REGIONAL CALIBRATION FACILITIES

The facilities that are available to assist in the move towards QA of UV measurements vary widely depending on location. National Metrology Institutes (NMIs) supply the irradiance standards upon which all calibrations are ultimately based, and have their own practices of intercomparison for the individually derived standards. Despite the care and attention to detail inherent in a NMI the resulting standards of UV spectral irradiance can differ significantly both within and between NMIs (see Global Overview).

Customers are not restricted to using only their own NMI, and nationality is no indication of the origin of the lamp standard against which an instrument has been calibrated.

Instrument calibration facilities provide a service that reverts to a standard lamp, albeit after several potential intermediate steps, and cannot avoid the basic absolute uncertainty due to the lamp. However, in principle they tie a group of instruments to one standard and so reduce the uncertainty in relative calibration amongst the group members. The group may be a regional network, a manufacturer's group (a set of one instrument type serviced by the manufacturer), or a set of otherwise unconnected individuals who happen to use the same calibration facility. The choice of facilities available will thus depend on a combination of location, instrument and funding.

WARNING: At present there is no regulation or external control on calibration centres or services, and the inclusion of a facility in this document must not be taken as endorsement of any of the services offered. The listings are for information only. It should also be noted that few of the facilities have full traceability, as defined by NMIs, to a particular NMI. In addition the facilities may refer themselves to any of the available NMIs, between which there are recognized differences in the UV standards of spectral irradiance. Thus, in terms of absolute calibration the facilities are not necessarily tied to each other in a formal way (see discussion of intercomparison for the sort of differences that may occur in the travelling standard instruments, for example). The customer is advised to check directly with any facility they wish to use to check the level of service provided, the level of QA practiced, the NMI to which the facility refers, and whether the facility is formally traceable to that NMI or not. The availability of such services may also change over time, with some ceasing to function while new facilities open. The listings below were last updated in the year 2002.

National Metrology Institutes are listed first, followed by instrument calibration facilities in the following regions: North America, Europe, Southern Hemisphere, Rest of the World.

4.1 National Metrology Institutes

The most important quantity (type of calibration) associated with solar UV measurements is spectral irradiance between 250 nm and 400 nm; the respective transfer and reference standards are tungsten-halogen lamps (in general 1kW FEL-type lamps). The following NMIs are capable of calibrating standards of spectral irradiance above at least 250 nm:

BNM-INM (Institut National de Metrologie, France)
CSIRO (Commonwealth Scientific and Industrial Research Organisation, Australia)
ETL (Electrotechnical Laboratory, Japan)
[NIM (National Institute of Metrology, People's Republic of China) large uncertainties, see CCPR intercomparison]
NIST (National Institute of Standards and Technology, USA)
NPL (National Physical Laboratory, UK)
[OMH (National Office of Measures, Hungary) only above 280 nm]
PTB (Physikalisch-Technische Bundesanstalt, Germany)
[SP (Sweden) traceable to NIST]
[VNIIOFI (All-Union Research Institute of Optical and Physical Measurements, Russia) large uncertainties, see CCPR intercomparison]
HUT (Helsinki University of Technology, Finland)
IRL (Industrial Research Ltd., New Zealand)

This list is based on the respective tables in the EC Calibration Brochure and on the results of the last CCPR intercomparison carried out between 1987 and 1990 (30). With the exception of the data of NIM and VNIIOFI, the relative uncertainties and differences of the NMI spectral irradiance scales in the UV are (expected to be) within ±3% (see Global Overview)

The next global intercomparison for standards of spectral irradiance above 250 nm, which is one of the CCPR Key Comparisons, started in 1999 (pilot laboratory: NPL). This intercomparison should provide better information about uncertainties and agreement between different NMIs.

Table 1: North American Establishments that Offer UV Calibration Services:

Agency	***Location***	***Type***	***Provide Service for* ...***
[1] Meteorological Service of Canada	Toronto, Ontario,Canada	Government Research Program	Canadian Brewer Network, other Brewer instruments
[2] Biospherical Systems Inc	San Diego, California, USA	Commercial Manufacturer	BSI Instruments/US National Science Foundation's Polar UV Monitoring Programme
[3] Central UV Calibration Facility	Boulder, Colorado, USA	Government Calibration Facility	All US Global Change Research Programs and other UV Monitoring Programmes
[4] Hoffman Engineering	Stamford, Connecticut, USA	Commercial Manufacturer	All Customers
[5] International Light	Newbury, Massachusetts, USA	Commercial Manufacturer	All Customers
[6] Li-COR, Inc.	Lincoln, Nebraska, USA	Commercial Manufacturer	All Customers
[7] National Institute of Standards	Gaithersburg, Maryland, USA	Government Calibration Facility	Public and Private Industry, Principle USA National Calibration Laboratory and Technology Institute
[8] Optronics	Orlando, Florida, USA	Commercial Manufacturer	All Customers
[9] Smithsonian Institute	Edgewater, Maryland, USA	Government Research Program	Smithsonian UV Research Projects
[10] Solar Light	Philadelphia, Pennsylvania, USA	Commercial Manufacturer	Solar Light Instruments
[11] Yankee Environmental	Turners Falls, Massachusetts, USA	Commercial Manufacturer	Yankee Instruments Systems

Service [19], under Europe below, also have a presence in North America.

*In this and the following tables the recipients of services have been identified if clearly defined. Some institutes (e.g. Universities, see European table) have the facilities to provide the services but may not routinely offer a commercial service, concentrating mainly on research projects within which such services may be offered.

4.2 North American Establishments

Services provided by North American Establishments (listed in Table 1):

In the tables below Secondary travelling standard refers to a portable lamp; mobile calibration facility refers to an instrument that can provide in situ comparisons with other instruments at their own sites; intercomparisons refers to a site suitable for large scale intercomparison campaigns. Absolute calibrations may be made in the laboratory against a lamp standard, or in the field using the sun as source and another well calibrated instrument as reference. See Annex 2 for further details of the definitions in the tables.

Establi-shment	Provide primary lamps	Sec'dry travl'ng standard	Spectral characterisation	Angular characterisation	Absolute calib. (lamp)	Absolute calib (sun)	Mobile calib. Facility	Intercomparisons
1			X		X	X	X	
2		X	X	X	X	X	X	
3*		X	X	X	X	X	X	X
4		X						
5		X						
6		X						
7$	X		X	X			X	
8		X						
9			X			X		
10			X	X	X	X		
11			X	X	X	X		

*CUCF is the primary UV calibration facility for US Global Change research programmes. Various US federal agencies have all signed a letter of intent to use this facility to coordinate UV calibrations.

$NIST is the US Government's top level standards organization providing calibration services, primary standards, standard methodologies and standards research for all commercial and public agencies in the US.

Full Address Listings:

[1] Meteorological Service of Canada
4905 Dufferin Street
Downsview, Ontario
M3H5T4 Canada
Contact: David Wardle
416-739-4632
David.wardle@ec.gc.ca

[2] Biospherical Instruments Inc.
5340 Riley Street
San Diego, California
92110-2621 USA
Contact: C.R. "Rocky" Booth
619-686-1888
Rocky@biospherical.com
http://www.biospherical.com

[3] Central UV Calibration Facility
NOAA R/E/Arx1
325 Broadway
Boulder, Colorado
80303 USA
Contact: Patrick Disterhoft
303-497-6355
Dister@srrb.noaa.gov
http://titan.srrb.noaa.gov

[4] Hoffman Engineering
Acosta Street
Stamford, Connecticut
06902 USA
Contact: Charla Everett
203-425-8900

[5] International Light 17 Graf Road Newbury, Massachusetts 01950 USA	Contact:	 978-465-5923 ilsales@intl-light.com
[6] Li-COR Inc. 4421 Superior Street PO Box 4425 Lincoln, Nebraska 68504 USA	Contact:	 402-467-3576 envsales@licor.com
[7] National Institute of Standards and Technology Building 220 Room A-305 Gaitherburg, Maryland 20899 USA	 Contact:	 Ambler Thompson 301-975-2333 Ambler@enh.nist.gov
[8] Optronics Laboratories 4470 35th Street Orlando, Florida 32811 USA	Contact:	was@olinet.com 800-899-3171 407-422-3171
[9] Smithsonian Institute Smithsonian Environmental Research Center (SERC) 647 Contee's Warf Road PO Box 28 Edgewater, Maryland 21037-0028 USA	Contact:	Douglass Hayes 301-261-4190 Hayes@serc.si.edu
[10] Solar Light Company Inc. 721 Oak Lane Philadelphia, Pennsylvania 19126-3342 USA	Contact:	Sol Berger 215-927-4206 http://www.solar.com
[11] Yankee Environmental Systems 101 Industrial Boulevard Montague Industrial Park Turner's Falls, Massachusetts 01376 USA	Contact:	Mark Beaubien 413-863-0200 http://www.yesinc.com

Table 2: European Establishments that Offer UV Calibration Services:

Agency	Location	Type	Provide services for…
[12] University of Innsbruck/ CMS Josef Schreder	Innsbruck, Austria	University/National Research	All customers (Schreder)
[13] Belgian Institute for Space Aeronomy (IASB)	Brussels, Belgium	Government Research Programme	
[14] Czech Hydrometeorological Institute Solar and Ozone Observatory	Czech Republic	Government Research Programme	
[15] Finnish Radiation and Nuclear Safety Authority (STUK)	Helsinki, Finland	Government Research Programme	
[16] Finnish Meteorological Institute	Helsinki, Finland	Government Research Programme	
[17] Scintec Atmospharenmesstechnik GmbH (now part of Kipp and Zonen, Netherlands, see below)	(Germany)		
[18] Forschungszentrum Karlsruhe (IMK-IFU)	Garmisch, Germany	Government Research Programme	DE spectrorad. network
[19] Gigahertz Optik		Commercial	All customers
[20] University of Hannover	Hannover, Germany	University	
[21] University of Thessaloniki	Thessaloniki, Greece	University	Greek UV network
[22] National Institute of Public Health and the Environment (RIVM)	de Bilt, Netherlands	Government Research Programme	
[23] Royal Netherlands Meteorological Institute (KNMI)	de Bilt, Netherlands	Government Research Programme	
[24] Institute for Metrology and Technology (NMI)	Netherlands	Government Research Programme	
[25] Kipp and Zonen	Delft, Netherlands	Commercial Manufacturer	Radiometers and Brewers
[26] Norwegian Institute for Air Research (NILU)	Kjeller, Norway	Commercial Manufacturer	Multifilter radiometers
[27] Norwegian Radiation Protection Authority (NRPA)	Osteras, Norway	Government Research Programme	NO multifilter network
[28] Swedish Meteorological and Hydrological Institute (SMHI)	Sweden	Government Research Programme	
[29] World Radiation Centre (WRC)	Davos, Switzerland	International Research Programme	Meteoswiss
[30] Bentham Instruments Ltd	Reading, UK	Commercial Manufacturer	All customers
[31] National Radiological Protection Board (NRPB)	Didcot, UK	Government Research Programme	NRPB network
[32] University of Manchester Institute of Science and Technology (UMIST)	Manchester, UK	University	

The following NMIs are also based in Europe:

[33] BNM-INM	France	Government Calibration Facility	
[34] Physikalisch-Technische Bundesanstalt	Germany	Government Calibration Facility	All customers
[35] OMH	Hungary	Government Calibration Facility	
[36] SP	Sweden	Government Calibration Facility	
[37] National Physical Laboratory	UK	Government Calibration Facility	All customers
[38] Helsinki University of Technology	Finland		

Services [1] and [10] (North America, above) are also used within Europe. Service [1] can be provided through service [25]. The Czech Republic, Hungary, Poland and Slovakia are planning a regional travelling Brewer standard traceable to [1].

4.3 European Establishments

Services provided by European establishments (listed in Table 2):

Establi-shment	Provide primary lamps	Sec'dry travl'ng standard	Spectral characteri sation	Angular characteri sation	Absolute calib. (lamp)	Absolute calib (sun)	Mobile calib. Facility	Intercomp arisons
12				X	X	X	X	
13			X	X	X			
14							X	
15			X	X	X	X	X	
16							X	
17(as23)								
18			X	X	X	X	X	X
19		X	X	X	X			
20		X	X	X	X		X	
21			X	X		X		X
22			X	X	X			
23					X	X		
24			X					
25			X	X	X	X	X	
26				X		X	X	
27			X	X		X	X	
28							X	
29				X		X		
30		X	X	X	X			
31						X	X	
32			X	X	X	X		
33	X							
34	X	X	X	X	X			
35	X							
36	X							
37	X	X	X	X	X			
38	X				X			

Full Address Listings:

[12] University of Innsbruck
Institute of Medical Physics
Muellerstr. 44
A-6020 Innsbruck, Austria
Contact: Mario Blumthaler
+43 512 507 3556
mario.blumthaler@uibk.ac.at
http://www.uibk.ac.at/projects/uv-index

Also in collaboration with:
Calibration Measurement Softwaresolutions
Oberndorf 116,
A-6322 Kirchbichl, Austria,
Josef Schreder,
+43 5332 77056
info@schreder-cms.com
http://www.schreder-cms.com

[13] IASB
3 Avenue Circulaire
B-1180 Brussels, Belgium
Contact: Didier Gillotay
dgill@oma.be

[14] Czech Hydrological Institute
Solar and Ozone Observatory
Contact: Michal Janouch
michal.janouch@chmi.cz

[15] STUK
Finnish Centre for Radiation and Nuclear Safety
P.O.Box 14
FIN-00881Helsinki
Finland
Contact: Kari Jokela
kari.jokela@stuk.fi

[16]	Finnish Meteorological Institute P.O.Box 503 FIN-00101 Helsinki Finland	Contact:	Tapani Koskela tapani.koskela@fmi.fi
[17]	see 25		
[18]	Forschungszentrum Karlsruhe (IMK-IFU) Kreuzeckbahnstrasse 19 82467 Garmisch-Partenkirchen Germany	Contact:	Stephan Thiel +49 8821 183 172 thiel@ifu.fhg.de
[19]	Gigahertz Optik Fischerstrasse 4, D-82178 Puchheim (Muenchen), Germany	Contact:	Anton Gugg-Helminger +49 (089) 89 01 59-0 a.gugg-helminger@ gigahertz-optik.com
[20]	University of Hannover Institute of Meteorology and Climatology Herrenhaeuser Str.2 30419 Hannover Germany	Contact:	Gunther Seckmeyer +49 511 762 4022 seckmeyer@muk.uni-hannover.de
[21]	University of Thessaloniki Laboratory of Atmospheric Physics 54124 Thessaloniki, Greece	Contact:	Alkis Bais +30 31 0998184 alkis.bais@auth.gr
[22]	National Institute of Public Health and the Environment (RIVM) Antonie van Leeuwenhoeklaan 9 Postbus 1 3720 BA Bilthoven The Netherlands	Contact:	Rick Tax rick.tax@rivm.nl
[23]	Royal Netherlands Meteorological Institute (KNMI) P.O.Box 201 Wilhelminalaan 10 3730 AE de Bilt The Netherlands	Contact:	Foeke Kuik kuik@knmi.nl
[24]	Institute for Metrology and Technology	Contact:	Charles Schrama cschrama@nmi.nl
[25]	Kipp and Zonen B.V. Rontgenweg 1 2624 BD Delft The Netherlands	Contact:	Henk van Renesse +31 15 2698013 +31 15 2620351 henk.van_renesse@kippzonen.com
[26]	Norwegian Institute for Air Research P.O.Box 100 Instituttveien 18 N-2027 Kjeller, Norway	Contact:	Arve Kylling +47 63 89 8000 arve.kylling@nilu.no
[27]	Norwegian Radiation Protection Authority (NRPA) P.O.Box 55 N-1332 Osteras, Norway	Contact:	Bjorn Johnsen bjorn.johnsen@nrpa.no +47-67-16-25-49 http://uvnett.nrpa.no/uv/
[28]	Swedish Meteorological and Hydrological Institute (SMHI)	Contact:	Weine Josefson weine.josefson@smhi.se

[29]	World Radiation Centre Davos Switzerland	Contact:	Rolf Philipona rolf.philipona@obsun.pmodwrc.ch
[30]	Bentham Instruments Ltd. 2 Boulton Road Reading RG2 ONH, UK	Contact:	Mike Clark +44 1189 751355 sales@bentham.co.uk
[31]	NRPB Chilton Didcot OX11 ORQ, UK	Contact:	Colin Driscoll +44 1235 822724
[32]	Departmentof Physics UMIST P.O.Box 88 Manchester, M60 1QD, UK	Contact:	Ann Webb +44 161 200 3917 ann.webb@umist.ac.uk
[33]	BNM-INM France	Contact:	J. Bastie bastie@cnam.fr
[34]	PTB Braunschweig Germany	Contact:	Juergen Metzdorf juergen.metzdorf@ptb.de
[35]	OMH H-1535 Budapest, Pf. 919 Hungary	Contact:	G. Deszi +36-1 458-5889. ugyfelszolg@omh.hu
[36]	SP Measurement Technology Box 857 SE-50115 BORÅS Sweden	Contact:	Gosta Werner +46 33 16 5451 gosta.Werner@sp.se
[37]	NPL Queens Road Teddington Middlesex TW11 OLW, UK	Contact:	Nigel Pearce Nigel.pearce@npl.co.uk
[38]	Helsinki University of Technology Metrology Research Institute P.O.Box 3000 FIN-02015 HUT Finland	Contact:	Petri Karha +358 9 451 2222 petri.karha@hut.fi

Table 3: Southern Hemisphere Establishments that Offer UV Calibration Services:

Agency	*Location*	*Type*	*Provide services for…*
[39] CSIRO	Australia	Government Research Facility	All customers
[40] Industrial Research Ltd. (IRL)	New Zealand	Government Research Facility	All customers
[41] National Institute of Water and Atmospheric Research Ltd. (NIWA)	New Zealand	National Research	UV researchers

Service [1] is also used in Japan to check calibration of their Brewer instruments.

CSIRO [39] is the NMI for Australia and IRL [40] is the NMI for New Zealand.

No facilities have been identified in South Africa. Service [2] is used in some South American countries

4.4 Southern Hemisphere Establishments

Services provided by Southern Hemisphere Establishments (listed in Table 3):

Establi-shment	Provide primary lamps	Sec'dry travl'ng standard	Spectral characteri sation	Angular characteri sation	Absolute calib. (lamp)	Absolute calib (sun)	Mobile calib. Facility	Intercomp arisons
39			X	X	X			
40			X		X			
41		X	X	X	X	X	X	X

Full Address Listings:

[39] CSIRO Division of Telecommunications and Industrial Physics
National Measurements Laboratory (NML)
Optics and Radiometry Project
Bradfield Road
West Lindfield 2070
Australia
Contact: Frank Wilkinson
61 2 9413 7300
Frank.Wilkinson@tip.csiro.au

[40] Industrial Research Ltd. (IRL)
PO Box 31-310
Lower Hutt
New Zealand
Contact: Kathy Nield
(64) 4 569 0000 (ext 4272)
K.Nield@irl.cri.nz

[41] National Institute of Water and Atmospheric Research Ltd. (NIWA)
Lauder,
PB 50061,
Omakau, Central Otago
New Zealand
Contact: Richard McKenzie
64 3 447 3411 (ext 829)
r.mckenzie@niwa.cri.nz

4.5 Rest of the World

Africa: GAW stations do not measure high resolution UVB. The broadband radiometers have never been "officially" calibrated by GAW.

China: GAW stations have Brewers that are tied to the Brewer calibration service [1], but calibration frequency is limited by funding.
NIM (People's Republic of China) for uncertainties, see CCPR intercomparison

Japan: National Institute of Advanced Industrial Science and Technology (AIST), Optical Radiation Section

Russia: The All-Russian Scientific Research Institute for Optical and Physical Measurements (VNIIOFI) (State Scientific Metrological Centre) for uncertainties, see CCPR intercomparison/BIPM key comparison data base

4.6 Quality Issues in Centralised Databases

The Network for the Detection of Stratospheric Change (NDSC) is a major contributor to the GAW programme. Its primary goal is to obtain high quality measurements of a broad range of stratospheric chemical species, aerosols and UV radiation, related to ozone loss and climate change. The NDSC provides quality criteria for the evaluation of UV spectroradiometers and measurement procedures, and this can be obtained from the NDSC web-page http://www.ndsc.ncep.noaa.gov/.

Other individual sites maintain their own data archives that may or may not be widely accessible to outside users. In addition, many sites also submit their data to central (regional or global) databases, in particular the World Ultraviolet Data Center (WUDC, held in Toronto for WMO as partner to the World Ozone Data Center), and the European Union Database that was established by the EC funded project SUVDAMA and is now being managed by a further project EDUCE. Both databases allow public access to the data on application, and both are developing means of defining the quality of data to the user. The activities associated with the two databases in this respect are described briefly below. While they are not always strictly QC or QA of the measurement process, as described in this document and the Guidelines for Quality Control (1) they do contribute to the overall quality assurance of data for the end user, who may not be familiar with measurement procedures that produce the data.

Both sites provide the facility for data providers to enter, and data users to see, metadata providing information about where and how the measurements were made, thereby aiding the process of establishing the quality of the data. It has been agreed by the SAG UV that European project data will be included in the WUDC.

The following statements have been provided by the project/database managers.

4.6.1 NDSC

In order to assure data quality, protocols have been established to guide and assist the activities of all NDSC investigators. The most important protocols related to QA are the data and validation protocols that include the following principles:

- All investigators place their preliminary measurement results in the NDSC archive via one of the NDSC Data Host Facilities as rapidly as possible, and no later than one year after being obtained.
- Since the nature of small trends detection requires an extremely high level of measurement confidence, the Data Protocol recognizes that multiple seasonal analyses may be required for observations from both individual and multiple sites. It is expected that such a procedure shall yield the verifiable product referred to as “NDSC data” within a two-year period after acquisition.
- Criteria for accepting new instruments that includes independent evaluation of the instrument design and data analysis and blind instrument and data analysis intercomparisons.
- Documentation criteria that include instrument and algorithm descriptions, validation procedures and history, and calibration procedures.
- Criteria for data quality that requires the investigator to be responsible for continuing instrument evaluation and routine data archiving, to participate in regular blind intercomparison campaigns, and to use standard methods of error analysis. Reports of continuing evaluation procedures are to be deposited in the NDSC archive.

4.6.2 EDUCE

A wide range of QA activities are planned within the EDUCE project. The scheduled tasks include: producing recommendations for QA procedures to be performed at measuring sites; an evaluation and review of various QC tools; the distribution of existing QC tools among institutes which plan to submit data to the database.

The central QA enterprise within EDUCE is the execution of a “quality audit”, to be performed at many of the EDUCE measuring sites.

The objectives of the quality audit are twofold. The primary objective is to verify the quality control procedures followed at sites which will submit data to the EDUCE database. The audit aims to provide assurance to users of the database that a certain level of quality has been achieved. (The purpose here is not to take responsibility for data management; data quality and quality control are, and remain, primarily the responsibility of the originator of the data). The site operator is expected to be able to present a detailed and comprehensive description of the calibration, measurement and data analysis procedures, together with the results of their customary application. The site operator should also be able to make a quantitative statement about the accuracy of the measurements and be able to justify this assessment. The second objective of the audit is to provide site operators with information that will allow them to improve the standard of their QC and QA procedures, and thus the value of their data. The final report will attempt to identify and promote best practice.

At least 10 different sites will be visited, with each visit lasting for a minimum of two full days. The audit will be executed according to a predefined checklist of questions and observations. The subjects covered will include the local environment and operating regime, calibration techniques and maintenance routines, measurement schedules and data analysis procedures.

Information about the QA tasks appearing within EDUCE can be found in the project's Description of Work and at the project's web site: http://www.muk.uni-hannover.de/EDUCE.

4.6.3 WOUDC

Data quality control and assurance is primarily the responsibility of the data originator. The purpose of the Site Scientific Sponsorship (SSS), which provides site information and is completed by every data provider, is to ensure and illustrate that the appropriate measures have been undertaken to provide high quality data for the inclusion into the WOUDC database. Once a file has been submitted to the WOUDC, data quality is monitored at various stages during data processing. Database quality control consists of checking for file format and metadata content, inspection of data value ranges and data redundancy checks.

Initially, a file will be tested for adherence to the file format specifications, but later, higher level statistical summaries may be generated, which identify anomalous values, calibration problems etc. Although the later examples involve more detailed knowledge of the data, the archive already includes enough data to make some critical judgments and general assessments about the data. As the volume and statistical knowledge increase, the scope of these assessments will be broadened.

The initial stages of the quality control path, how the files are checked, what happens to the original data and what sort of data flagging occurs are described below.

General principles of the WUDC Identification of Data Quality

There are four basic elements in the quality control of WUDC data. These are:

1. Acceptance of the Data Passport or SSS.

2. Examination by the WUDC. Data are checked for file format, presence of required meta data and valid value ranges.

3. Examination by External groups.

4. Additional QA/QC by the WMO and MSC Advisory Committees.

The first is the joint responsibility of the originator and the WUDC while the second is an examination of the data solely by the WUDC. The third and fourth elements are not strictly defined and are expected to evolve. Data that have passed through the first two elements are published on the WOUDC ftp server.

The Data Passport or SSS

The single most important step in the quality control process is the acceptance of the Data Passport or SSS. Guidelines for quality control with regards to the SSS have been established and published by the WMO/GAW Scientific Advisory Group on Ultraviolet radiation (SAG UV) [3]. In addition, examples of SSS documents can be examined on the WOUDC ftp server and Web site. The subjects to be covered are, therefore, well established. However, the writer of the SSS need not follow a rigid prescription. The contents of the SSS are discussed in Section 5.1 of the "Guide to the WMO/GAW World Ultraviolet Radiation Data Centre" (WOUDC Guide) to be found through http://www.woudc.org/data/UsingArchive_e.html.

Examination by the WOUDC

Once a file arrives at the WOUDC, the data are first checked for adherence to the correct format and content rules established in Section 5.3 of the WOUDC Guide. Only those files that meet the metadata requirements are to be indexed in the WUDC database. It is not necessary for all files to conform to the extCSV file format, provided that the required metadata can be extracted from the file.

Examination of data values includes the identification of obvious errors such as misprints or data transmission errors. Data values are range checked and any anomalous values are further examined. When the data have been processed through the initial stages, output files ready for posting on the ftp site may include an additional data index (flag) which is aimed at providing the data client with information about any unusual or anomalous values of the data itself or derived properties of the spectrum.

Additional Data Quality Identification Procedures

An additional data index (flag) has been established for WUDC output data products. The aim is to provide information about unusual or anomalous values or a more detailed description of other useful characteristics. Each flag is a separate digit and can have values in the range 0-3 inclusive. Code 0 indicates that the value of the relevant property is in the usual range of values for that property while the codes 1, 2 and 3 indicate increasingly unusual values. The interpretation is as follows: Code 0 means no problems or potential problems were found, Code 1 means that there may be a minor problem with the data. Normally, 3-5% of all data have Code 1. Code 2 shows either unusual observing conditions or some problem with the instrument. The percentage depends on the criteria and is different for the various flags. Code 3 shows a major disturbance in the data (property) that the "user" should definitely know about. While Codes 1, 2 and 3 raise the possibility of instrument malfunctions, it is important to note that spectra with known significant instrument problems have already been rejected. However, instrument problems cannot be considered to be eliminated from these data.

Examination by Others

The WOUDC has benefited considerably from research done by users of the data and expects to continue to do so. The user may find aspects of the data and deficiencies that are entirely unexpected by the originator. Notification of the WOUDC can produce better data processing and comments; references and/or papers by users can be included in the WOUDC.

Role of WMO and MSC Advisory Committees

Advisory Committees can help the WUDC in a number of ways. The MSC committee has special expertise in the management of related data centres. The WMO/GAW SAG UV has a wide base of experience in many aspects of UV radiation and has the task of coordinating UV measurement activities for the WMO globally. As well as providing advice on techniques and requirements, the people on these committees can assist WUDC by being model or test clients, that is originators and users of data, and by promoting the use of the centre. Finally, the committees can ratify or not ratify critical scientific decisions made by WUDC staff or more generally to help WUDC make such decisions. This might be particularly important with regard to decisions to accept or reject submitted data. More information can be found at http://www.woudc.org

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ANNEX 1

Strategy for the Implementation of the Global Atmosphere Watch Programme (2001-2007)
UV Measurements

The GAW UV Programme Goals are:

- To further the development and co-ordination of the GAW UV radiation monitoring network.
- To establish a UV climatology, i.e. a knowledge of average levels of UV doses and UV variations on a world-wide ba ss.
- To develop a reliable database of UV observations for use in UV effects studies.
- To increase public awareness of UV changes and potential effects of UV exposure.
- To define and promote the implementation of operational structures for quality control, quality assurance, data archiving and the ancillary measurements needed for data analysis.
- To establish relationships with other agencies, user communities, and scientific programmes dealing with UV radiation.
- To refine statements of the need within GAW for solar radiation data relating to the infrared and visible spectrum and, in particular, to identify the interfaces with the BSRN and WWW programmes.

The SAG for UV Solar Radiation web page can be found at
http://www.wmo.ch/web/arep/gaw/sag.html

Terminology

In order to discuss the issue of traceability, it is essential that the metrological terminology is clearly and consistently defined. At present relatively common terms are frequently misinterpreted and misused when applied to metrology, causing lack of clarity and understanding. The following (see table below) are formal, internationally agreed definitions [1] and it is recommended that they are adopted in the GAW programme.

Other terms requiring clear definition are those given in the tables of calibration facility services. These are defined as follows:

Primary lamps - lamps directly calibrated against a defined source of spectral irradiance (e.g. a black body). Normally only available from National Standards Laboratories.

Secondary traveling standard - a portable lamp carrying the standard of spectral irradiance held by the facilities highest standard lamp.

Spectral characterization - definition of the spectral response of the instrument. For broadband instruments this is the relative sensitivity to all wavelengths to which the instrument responds. For spectroradiometers it is the slit function (incorporating the full width half maximum, FWHM), and should be tested at several wavelengths. In both cases sensitivities several orders of magnitude below the peak sensitivity may be important, especially at longer wavelengths, and the tests should cover 5-6 orders of magnitude.

Angular characterization - definition of the angular response of the instrument under test. This is usually supposed to be a cosine response but may be an alternate response e.g. actinic flux (unweighted). The angular response should be tested across at least two orthoganol planes and at several wavelengths for a spectral instrument.

Absolute calibration (lamp) - calibration to the standard held by a lamp standard of spectral irradiance.

Absolute calibration (sun) - calibration provided against a well-calibrated instrument by comparison of simultaneous measurements with the instrument undergoing calibration, using the sun as source, at the facility site.

Mobile calibration facility - a well-calibrated instrument that can be moved to other sites to provide *in situ* comparisons with other instruments at their home sites.

Intercomparisons - the facility has available a site suitable for large scale intercomparison campaigns in which many instruments measure the solar radiation simultaneously and from the same platform.

[1] International Vocabulary of Basic and General Terms in Metro logy. Pub. International Standards Organisation (ISO), 1993.

SI units	- **The coherent system of units adopted and recommended by the General Conference of Weights and Measures (CGPM).**
Accuracy of measurement	- **Closeness of the agreement between the result of a measurement and a true value of the measurand.**
Precision	- **No metrological definition except to state that it should never be used in the context of "accuracy"and, because of possible confusion its use, should normally be avoided in metrological applications.**
Repeatability of results of measurements	- **Closeness of the agre ement between the results of successive measurements of the same measurand carried out under the same conditions of measurement.**
Reproducibility of results of measurements	- **Closeness of the agreement between the results of measurements o f the same measurand carried out under changed conditions of measurement.**
Uncertainty of measurement	- **Parameter, associated with the result of a measurement, that characterises the dispersion of the values that could reasonably be attributed to the measurand**
Error of measurement	- **Result of a measurement minus a true value of the measurand**
Stability	- **Ability of a measuring instrument to maintain constant its metrological characteristics with time.**
Traceability	- **Property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually througl an unbroken chain of comparisons all having stated uncertainties.**

Contact addresses

Lead author:

Dr Ann R. Webb
Department of Physics
UMIST
P.O. Box 88
MANCHESTER, M60 1QD
United Kingdom
Tel.: 44 0 161 200 3917
Fax: 44 0 161 200 3941
e-mail: ann.webb@umist.ac.uk

World Ultraviolet Radiation Data Centre (WUDC):

Meteorological Service of Canada
4905 Dufferin Street
NORTH YORK, Ontario
Canada M3H 5T4
e-mail: woudc@ec.gc.ca
WWW access: http://www.msc-smc.ec.gc.ca/woudc

WMO Secretariat:

Dr Liisa Jalkanen
World Meteorological Organization
7 bis, avenue de la Paix
Case Postale No. 2300
1211 GENEVA 2
Switzerland
Tel.: 41 22 7308 587
Fax: 41 22 7308 049
e-mail: LJalkanen@wmo.int

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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

49. Proceedings of the WMO Conference on Air Pollution Modelling and its Application (Volumes I-III), Leningrad, USSR, 19-24 May 1986. November 1987 (WMO TD No. 187)

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

54. Global Atmospheric Background Monitoring for Selected Environmental Parameters. BAPMoN Data for 1983, Volume II: Precipitation chemistry, continuous atmospheric carbon dioxide and suspended particulate matter (WMO TD No. 283)

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)

67. Report of the Meeting of Experts on Modelling of Continental, Hemispheric and Global Range Transport, Transformation and Exchange Processes, Geneva, 5 -7 November 1990

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)

72. Integrated Background Monitoring of Environmental Pollution in Mid-Latitude Eurasia by Yu.A. Izrael and F.Ya. Rovinsky, USSR (WMO TD No. 434)

73. Report of the Experts Meeting on Global Aerosol Data System (GADS), Hampton, Virginia, 11 to 12 September 1990 (WMO TD No. 438)

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

78. Global Atmospheric Background Monitoring for Selected Environmental Parameters BAPMoN Data for 1990, Volume I: Atmospheric Aerosol Optical Depth (WMO TD No. 446)

79. Report of the Meeting of Experts to Consider the Aerosol Component of GAW, Boulder, 16 to 19 December 1991 (WMO TD No. 485)

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)

88. Report of the Seventh WMO Meeting of Experts on Carbon Dioxide Concentration and Isotopic Measurement Techniques, Rome, Italy, 7 - 10 September 1993, (edited by Graeme I. Pearman and James T. Peterson) (WMO TD No. 669)

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

90. Global Atmospheric Background Monitoring for Selected Environmental Parameters GAW Data for 1992, Volume I: Atmospheric Aerosol Optical Depth (WMO TD No. 562)

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)

93. Report of the Third WMO Meeting of Experts on the Quality Assurance/Science Activity Centres of the Global Atmosphere Watch, Garmisch-Partenkirchen, 5-9 July 1993 (WMO TD No. 581)

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

95. Report of the WMO Meeting of Experts on UV-B 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 UV-B 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)

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

114. Report of the Fifth WMO Meeting of Experts on the Quality Assurance/Science Activity Centres (QA/SACs) of the Global Atmosphere Watch, jointly held with the Second Meeting of the Coordinating Committees of IGAC-GLONET and IGAC-ACE[Ed], Garmisch-Partenkirchen, Germany, 15-19 July 1996 (WMO TD No. 787)

115. Report of the Meeting of Experts on Atmospheric Urban Pollution and the Role of NMSs (Geneva, 7-11 October 1996) (WMO TD No. 801)

116. Expert Meeting on Chemistry of Aerosols, Clouds and Atmospheric Precipitation in the Former USSR (Saint Petersburg, Russian Federation, 13-15 November 1995)

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)

120. WMO-UMAP Workshop on Broad-Band UV Radiometers (Garmisch-Partenkirchen, Germany, 22 to 23 April 1996) (WMO TD No. 894)

121. Report of the Eighth WMO Meeting of Experts on Carbon Dioxide Concentration and Isotopic Measurement Techniques (prepared by Thomas Conway) (Boulder, CO, 6-11 July 1995) (WMO TD No. 821)

122 Report of Passive Samplers for Atmospheric Chemistry Measurements and their Role in GAW (prepared by Greg Carmichael) (WMO TD No. 829)

123 Report of WMO Meeting of Experts on GAW Regional Network in RA VI, Budapest, Hungary, 5 to 9 May 1997

124 Fifth Session of the EC Panel of Experts/CAS Working Group on Environmental Pollution and Atmospheric Chemistry, (Geneva, Switzerland, 7-10 April 1997) (WMO TD No. 898)

125. Instruments to Measure Solar Ultraviolet Radiation, Part 1: Spectral Instruments (lead author G. Seckmeyer) (WMO TD No. 1066)

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)

131. WMO Workshop on Regional Transboundary Smoke and Haze in Southeast Asia (Singapore, 2 to 5 June 1998) (Gregory R. Carmichael). Two volumes

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)

136. WMO/EMEP/UNEP Workshop on Modelling of Atmospheric Transport and Deposition of Persistent Organic Pollutants and Heavy Metals (Geneva, Switzerland, 16-19 November 1999) (Volumes I and II) (WMO TD No. 1008)

137. Report and Proceedings of the WMO RA II/RA V GAW Workshop on Urban Environment (Beijing, China, 1-4 November 1999) (WMO-TD. 1014) (Prepared by Greg Carmichael)

138. Reports on WMO International Comparisons of Dobson Spectrophotometers, Parts I – Arosa, Switzerland, 19-31 July 1999, Part II – Buenos Aires, Argentina (29 Nov. – 12 Dec. 1999 and Part III – Pretoria, South Africa (18 March – 10 April 2000) (WMO TD No. 1016).

139. The Fifth Biennial WMO Consultation on Brewer Ozone and UV Spectrophotometer Operation, Calibration and Data Reporting (Halkidiki, Greece, September 1998)(WMO TD No. 1019).

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).

142. Strategy for the Implementation of the Global Atmosphere Watch Programme (2001-2007), A Contribution to the Implementation of the Long-Term Plan (WMO TD No.1077)

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).