Final Publishable JRP Summary for ENV03 SolarUV
Traceability for surface spectral solar ultraviolet radiation

Overview

This project has made significant improvements in spectral global solar ultraviolet measurements by decreasing the uncertainty of the world reference spectroradiometer, improving the characterisation of array spectroradiometers, establishing a new portable UV reference spectroradiometer and developing new technologies, methods and software for applications in the solar UV end-user community responsible for environmental and human health protection.

Need for the project

The reliable quantification of UV radiation at the Earth's surface requires accurate measurements of spectral global solar UV irradiance in order to understand the expected long-term trends in this parameter (of about 2% increase per decade). The observation and understanding of the climatic trend is essential mainly for human health protection for the next several decades. An increase in surface UV radiation can substantially increase additional non-melanoma and melanoma skin cancers and can cause more than a million additional cases of yearly cataracts worldwide. In prevention of some diseases UVB has beneficial health effects due to vitamin D production in the human body.

Therefore, balancing the risks and benefits of solar UV radiation is a challenge for policymakers and health advisors, which requires reliable measurements on which to base decisions by law makers. Currently, terrestrial measurements of spectral solar UV radiation are limited to a few places worldwide, where spectral solar UV monitoring instruments are located. In this context, UV monitoring at additional locations with traceable uncertainty is required to better understand the relationship between UV radiation and its influencing factors and to validate radiative transfer models from research institutes and satellite-derived UV estimates.

In order to support health protection agencies, national atmosphere observation and international research institutes, improved UV measuring instrumentation is needed i.e. scanning spectroradiometers and array spectroradiometers with reduced uncertainty and a new traceability chain for calibration. In particular array spectroradiometers provide cost effective alternatives for spectral irradiance measurements and provide the potential to increase the worldwide UV monitoring network. To ensure the quality of array spectroradiometers, the instruments need to be characterised using a costly infrastructure typically only available at NMIs. The end-user community - following the objectives above - has not the experience and the infrastructure to thoroughly characterise their array spectroradiometers. Even more, the joint research project aimed to establish collaborations between the NMI and the end-users for support with newly developed techniques, methods and guidelines to ensure the quality of their measurements.

Scientific and technical objectives

To achieve the end-user need described above, the project aimed at shortening the traceability chain of solar UV measurements to the SI unit and to reduce the associated transfer uncertainties e.g. for the portable world reference spectroradiometer known as 'QASUME' from 5% to between 2 % and 3%. Furthermore, the project aimed at developing characterisation procedures for array spectroradiometers in UV monitoring networks, where significant progress is needed to obtain reliable solar UV measurements with these cost-effective devices. Therefore, new technologies, characterisation techniques and post-correction methods were needed to determine and physically reduce the impact of stray light and to correct the influence of stray light, linearity, and wavelength scale when using array spectroradiometers.

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Specifically, the following four scientific and technical issues were addressed to achieve the main objectives:

1. Improving spectral irradiance traceability of spectroradiometers:
    - Upgrading and expanding the existing tuneable laser suite at PTB, to enable the absolute calibration of spectroradiometers,
    - Development of compact, robust, portable and stable UV LED-based monitoring sources that are suitable for field use,
    - Development of a transfer standard based on a compact laser-induced UV source, also suitable for field calibrations.
2. Improving array spectroradiometer characterisation:
    - Development of guidelines for measuring solar UV spectra using array spectroradiometers,
    - Development of an algorithm/methodology for stray light correction and an algorithm/methodology for bandwidth and wavelength correction methodology. To provide quality ensured solar UV spectra for worldwide comparison,
    - Development and evaluation of two devices for wavelength scale characterisation and three methods for determining linearity of array spectroradiometers.
3. Development of an improved QASUME reference UV spectroradiometer:
    - Improvement of the existing QASUME UV spectroradiometer, with a new global entrance optic to measure the spectral solar irradiance,
    - Development of a new solid-state detector as a replacement for the existing photomultiplier,
    - A feasibility study on the suitability of a Fourier-Transform spectroradiometer to be used for solar UV irradiance measurements.
4. Investigating the suitability of new technologies for solar irradiance measurements:
    - Development of a UV hyperspectral imaging camera for spectral sky radiance measurements and to optimise global entrance optics for solar UV irradiance measurements,
    - Development and testing of two prototype UV array spectroradiometers with improved stray light rejection using 1) micro-mirror devices and 2) band-pass filters.

Results

Improving spectral irradiance traceability of solar UV measurements

One of the main goals within the project was the realisation of a detector-based traceability chain of spectral irradiance in order to shorten the traceability chain to the primary standard of optical power and thereby significantly reduce the uncertainties for spectral irradiance calibrations. In order to reach this goal, an upgraded and expanded existing tuneable laser source was required to provide sufficiently high irradiance power.

The upgraded and expanded existing tuneable laser source was developed and the new traceability chain tested with the World reference spectroradiometer QASUME of the World Calibration Center for UV (WCC-UV). As a result the radiometric uncertainty of the QASUME spectral irradiance was decreased from ±4% to ±1.5 %. The work demonstrated that the traceability chain can be shortened and calibration uncertainties considerably reduced in the laboratory by using the upgraded facilities at the involved National Metrology Institute.

Solar UV measurements take place outdoors, far from metrological laboratories, and therefore calibration devices are needed to verify the correct operation of the deployed spectroradiometers under challenging environmental conditions. Two devices were developed for this purpose:

Firstly, a portable UV monitoring source based on Light Emitting Diode (LED) technology was developed. The consortium constructed and tested a prototype monitoring source built of purpose selected UV-LEDs. The portable UV-LED device was successfully operated at several field campaigns, such as in La Reunion Island and El Arenosillo, Southern Spain, to monitor the stability of the QASUME spectroradiometer and to provide a traceable link to SI. The performance of the prototype device has reached a stage where a commercial version can be manufactured by interested companies.

Secondly, a transfer standard based on a Laser Driven Light Source (LDSL) was developed as an alternative portable reference for absolute calibration of spectroradiometers in the field. The main advantage of the LDLS with respect to monitoring devices as mentioned previously is its use as a free-space radiation source, thereby allowing the direct traceability of a solar UV spectroradiometer without the necessity of an additional laboratory calibration.

In summary, solar UV irradiance measurements are now possible with significantly reduced uncertainties, and the devices and methodologies developed in this project are available to the end-user community.

Improving array spectroradiometer characterisation

In order to structure and summarise the required procedure to properly operate array spectroradiometers “A guide to measuring solar UV spectra using array spectroradiometers” was developed by several project partners and is published on the project web-page to remain accessible to the end-user community after the end of the project. The document will also be stored in the coordinator’s archive to be sent out on request. In addition to the general guideline, “A guide for the evaluation of the solar spectrum measurement uncertainty using array spectroradiometers” was developed by a project partner and tested by several research partners and end-users during the final intercomparison in July 2014 in Davos.

One of the highest uncertainty components in the measurements by array spectroradiometers in the solar UV spectral range is caused by stray light within the instrument. A reduction of this unwanted radiation by more than 90% was achieved with two array spectroradiometers using a correction matrix based on line spread functions that was determined with the help of spectrally tuneable lasers. The methodology and results were published in the peer-reviewed literature.

Accurate wavelength calibration is a key parameter for solar spectral measurements. The aimed uncertainty is below 50 pm. Commonly, spectrometers are calibrated with spectral emission lines. However, for the solar UV spectral range only a few lines are typically available. Within this project two different approaches were realised that allow characterisation of the wavelength scale accurately throughout the UV (and visible) spectral range: 1) based on a Fabry-Perot etalon, 2) based on a one-stage Lyot filter. Due to the research and development undertaken within this project, both devices may lead to a commercial product, if a sufficiently stable alignment and temperature control can be provided by an interested manufacturer.

The linearity of the data acquisition of array spectroradiometers is crucial due to the large dynamic range of the solar UV radiation. Within the framework of this project, new approaches to the linearity characterisation of array spectroradiometers were developed at four partners’ institutes. The results from the four methods agreed very well and were presented at several international workshops.

The software tool “matSHIC” was developed in order to homogenise solar spectra from array spectroradiometers (nominal spectral resolution and traceable wavelength scale). This software tool is available free of charge and has been distributed to several end-users who have implemented this tool in their data processing chain.

Development of an improved QASUME reference UV spectroradiometer

Several devices were developed within this project to improve solar UV measurements with spectroradiometers. These devices were implemented on the reference spectroradiometer system QASUME-II and its performance evaluated with respect to the original QASUME-I system. As shown below, QASUME-II is able to measure solar UV irradiance with lower uncertainties than QASUME-I.

First, new types of entrance optics for global irradiance measurements were developed to reduce the cosine error of the optics using new material and geometry. The new diffusers are based on novel quartz-based materials that were extensively studied with a dedicated modelling software developed in the frame of this project. The new diffusers are available commercially from two industrial partners and the software can be ordered on request.

Second, the data acquisition system of QASUME-II was modified to resolve instabilities observed with current detection systems based on photomultipliers, by implementing a hybrid system consisting of a photomultiplier combined with a solid state detector.

An alternative approach to scanning double monochromators as used in the QASUME spectroradiometer was investigated by adapting a Fourier transform spectrometer for solar UV measurements. The device was characterised with respect to spectral resolution, responsivity, stability, dynamic range and systematic distortions. Differently to QASUME, the device allows determination of solar UV spectra with a narrower bandwidth and with an inherent SI traceable wavelength. A comparison between QASUME and this instrument demonstrated the potential capabilities of such an approach, even though the sensitivity in the UV range needs to be significantly enhanced in the current system.

Investigating the suitability of new technologies for irradiance measurements

A novel instrument has been designed, realised and tested to provide information on the sky radiance distribution in the sky. The hyperspectral camera is able to observe the entire sky with high spatial resolution generating a calibrated emissivity spectrum in the UV range for each point of the image at a given time. The developed, characterised and tested instrument is now available for scientific investigations in the field of solar UV observations.

Several methods to reduce stray-light in array spectroradiometer systems were investigated using novel techniques. The first study led to the construction of a prototype instrument based on micro-mirror array devices. A second study implemented band pass filters in an array spectroradiometer using two entrance optics joined by a bi-furcated optical fiber. Both developments are in a prototype stage and in the future may be adopted and implemented by instrument manufacturers to improve their products.

Actual and Potential Impact

Dissemination activities

The research output was mainly disseminated to the end-user community by several training events and via newsletters during and at the end of the project. These included

- three workshops,
- several seminars,
- on site visits during operational quality assurance campaigns,
- an instrument intercomparison at the end of the project.

These activities are key to ensuring the improvement of long-term solar UV trend monitoring by international research institutes, national meteorology institutes and health protection agencies.

In order to impact on regulation bodies, the project was represented in several standard committees, while the scientific results were published in 16 papers in international journals and 63 oral or poster presentations.

In order to additionally focus on the stakeholder needs, the project partners also disseminated their achievements in 2 Newsletters, UVnews 9 and UVnews 10, of the Thematic Network for Ultraviolet Measurement, UVNet (http://metrology.hut.fi/uvnet/). More than 250 subscribers appreciated the novel approaches in the field of solar UV measurements and the established mailing list will be used in future to ensure a continuous communication for a long-term impact of the project.

Early impact

Training & intercomparison: One major impact of the project was the UV intercomparison held at Davos, Switzerland from 7 to 16 July 2014, which led to the dissemination of the techniques to the end-user community. The intercomparison was attended with 25 instruments from participants of the user community such as:

- Public Health Agency
- Medical University
- Environmental University
- Environmental Protection Agency
- National Meteorology Institutes
- Industry

The participants were trained during the intercomparison using the new technologies and methods to improve their solar UV measurements in the field and ultimately will improve the delivery of their public duties as intended by the project.

Moreover, in a preparation for the comparison some of the users gained access to laboratory facilities of NMIs providing them a chance to receive a detailed characterisation of their instruments. The joint training with the tools and devices developed during the project were well received and the feedback from the user community was very encouraging. The revised UV measurements, based on calibrations and characterisations performed with the tools and techniques developed in the project, produced significantly improved spectra, demonstrating the value of the project’s results to everyone attending the intercomparison. This collaboration was a unique opportunity to establish personal contacts between the NMIs and the end-user community and will contribute to impact in the longer-term as the improved measurement methods and skills are adopted in the field.

Scientific: The main podium for reaching the end-users from the scientific community specifically working with solar UV instruments were the three workshops held in 2012, 2013 and 2014. The impact provided by these workshops was important also from a long-term perspective in reinforcing the importance of the UV community within the larger radiation and environmental science community (e.g. first UV session at the International Radiation Symposium 2012 in conjunction with the workshop) and the relevant stakeholders.

Social: The coordinating role of SFI DAVOS confirmed and strengthened the position of SFI Davos as the World Calibration Center for UV radiation (WCC-UV) on behalf of the World Meteorological Organization (WMO). In this context, the upgraded QASUME reference spectroradiometer now provides a second portable reference standard for the quality assurance of solar UV irradiance of solar UV monitoring sites at a global level.

Economic: Industry (project partners and external) was supported by the development of new prototype devices and tested methods to improve their existing spectroradiometers and to develop potentially new spectroradiometers. The global entrance optics are available from two commercial companies to the end-user community. Furthermore, this technological impact can also be applied to industrial applications outside of the solar UV community.

Potential impact

The robust and cost-effective array spectroradiometers that will eventually be deployed as instruments in UV monitoring networks will be a unique European contribution to the topic of climate change and the challenges of addressing changes in solar UV radiation and its long-term effect on populations in terms of human health effects.

The social impact is expected to occur from the dissemination of the project's results and recommendations to the relevant standard bodies. For example, the technical committee TC2-51 of CIE received the "guide to measuring solar UV spectra using array spectroradiometers" for preparing a document on the calibration, characterisation and use of array spectroradiometers. Moreover, the CIE-60 and TC2-17 appreciated the recommendations at the end of this project. The project was further invited to present at the WMO TECO conference, which helps to facilitate long-term impact in the world meteorology community.

Economics: Due to the efforts of the project, it became evident that a thorough characterisation of array spectroradiometers is needed both for measuring solar and artificial radiation sources. The project consortium therefore recommended that NMIs should provide new characterisation and calibration services, such as tuneable laser sources for line spread function measurements and linearity determination or the shortened traceability chain for laboratory calibration.

Specifically, this project has:

- Reduced uncertainty of the primary reference spectroradiometer QASUME, which will provide improved traceability to UV monitoring stations and thereby better understanding of decadal UV changes,
- Validated fast solar UV irradiance spectra measurements, which will enable determination of cloud effects on spectral UV radiation and under rapidly changing conditions,
- Developed stray-light and bandwidth correction methods for characterised array spectroradiometers, which allow the use of these robust and cost-effective instruments for UV exposure studies with known uncertainties,
- Developed global input optics and solid state detectors, to significantly decrease the measurement uncertainties of spectroradiometers from the end-user community,
- Significantly increased awareness among the user-community of the necessity of a thorough characterisation of array spectroradiometers before they are used for solar UV measurements.

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