Publishable Summary for 19ENV04 MAPP
Metrology for aerosol optical properties

Overview

The overall aim of this project was to enable the SI-traceable measurement of column-integrated aerosol optical properties retrieved from the passive remote sensing of the atmosphere using solar and lunar radiation measurements. In order to validate and improve the current aerosol optical property retrievals using state-of-the-art inversion models, radiometers of the three largest aerosol monitoring networks were calibrated at NMI laboratories, and portable devices for the in-field calibration of network radiometers were developed. Comprehensive uncertainty estimates for the column averaged aerosol optical properties were developed, to underpin the measurements of the three global networks involved in this project. These aerosol uncertainty calculations were implemented in the inversion code GRASP which is a publicly available code to the scientific community to retrieve aerosol optical properties from solar irradiance measurements. The top of the atmosphere solar spectrum TSI-1 HSRS was validated with respect to traceable ground-based measurements to provide a validated and traceable solar spectrum to use for aerosol optical depth retrievals from calibrated solar irradiance measurements.

Need

Global climate assessments require harmonised and quality-controlled datasets. This implies measurements preferably traceable to the SI and cross-network wide implementations of calibration and post-processing procedures.

Atmospheric aerosols are minor constituents of the atmosphere, but a critical component in terms of impacts on the climate. Their properties have been recognised as **Essential Climate Variables (ECVs)** by the Global Climate Observing System (GCOS). As pointed out in all previous IPCC (Intergovernmental Panel on Climate Change) reports, aerosols continue to contribute the largest uncertainty to estimates and interpretations of the Earth's changing energy budget.

Long-term monitoring of aerosol ECVs including their uncertainties is needed for observing sensitive changes in the Earth climate system. Currently the three main global surface-based networks measuring column integrated aerosol optical properties in Europe, AERONET Europe, GAW-PFR and SKYNET Europe, operate over hundred stations with complex calibration strategies based on artefact reference devices. The lack of an appropriate metrological framework in the calibration, operation, and data processing of these networks rendered the whole monitoring concept very convoluted, time consuming, labour intensive, and uncertain.

Calibrations of reference radiometers have been performed at only two stations world-wide (Mauna-Loa, Hawaii or Izaña, Tenerife). The subsequent calibration of network radiometers were based on such reference artefacts relies on instrument stability and instrument redundancy and not on objective metrological concepts. The field calibration procedure of calibrating network radiometers at centralised calibration stations outdoors requiring perfect weather conditions meant long calibration times and therefore excessive downtime at monitoring stations.

Emerging technologies such as compact array spectroradiometers or portable Fourier spectrometers offer the potential for enhanced atmospheric products providing significantly more information on the radiative forcing impact on climate.

The need for an objective assessment of uncertainties of the retrieved aerosol properties is an inherent property of traceable measurements, which was lacking in all three main global aerosol monitoring networks. The databases providing access to the network data did not offer concurrent uncertainty estimates.

Objectives

The overall goal of this project was to enable the SI-traceable measurement of column-integrated aerosol optical properties (ECVs) for assessing the radiative forcing impact on the climate. These properties were retrieved from the passive remote sensing of the atmosphere using solar and lunar radiation measurements that were largely lacking traceability to the SI. The specific objectives of the project were:

1. To develop calibration methods and traceable devices for SI-traceable laboratory and in-field calibrations for radiometers measuring direct solar spectral irradiance and sky radiance, in the spectral range 310 nm up to 1700 nm with an expanded uncertainty of 1 %. Instruments measuring lunar irradiance were included into the scope of the objective following the expressed needs of the stakeholders.
2. To validate the methods for zero airmass extrapolation by means of traceable ground-based solar spectral irradiance measurements and comparison to satellite-based solar extra-terrestrial spectra. Due to the growing importance of lunar irradiance measurements to retrieve AOD during night-time conditions (e.g. polar winter), validations of lunar irradiance phase models were also addressed.
3. To develop a comprehensive uncertainty budget for aerosol optical properties, such as aerosol optical depth, aerosol size distribution, and aerosol single scatter albedo, retrieved from remote sensing-based measurements of direct and scattered solar radiation, enabling its inclusion in the corresponding data archives of the aerosol monitoring networks, with the relevant calibration and traceability information.
4. To facilitate the take-up of the developed technology and measurement infrastructure developed in the project by the measurement supply chain (NMIs, DIs, and calibration laboratories), standards developing organisations (WMO CIMO, WMO GAW SAG) and end users (e.g. ground-based and space-based remote sensing and atmospheric science communities). In addition, to support the European Metrology Network for Climate and Ocean Observation.

Progress beyond the state of the art

Current aerosol optical remote sensing networks rely either on a strict calibration hierarchy, based on bilateral comparisons between network and reference instruments (GAW-PFR and AERONET), or on in-situ calibrations of network radiometers without any link to traceable standards (SKYNET). The traceability of the GAWPFR and AERONET networks rely on the stability of the reference radiometers and furthermore, on the scheduled re-calibrations of the network radiometers, which can last for several months, resulting in significant data gaps in the measurement series. To address these limitations, this project developed procedures and devices to provide laboratory-based calibrations with traceability to SI.

Tuneable laser sources are revolutionising radiometric calibrations. Due to their high costs and operational complexity they are still, however, only used by very few laboratories. The project provided access to the tuneable laser facilities at PTB, VSL, NPL, and SFI Davos for characterising the spectral bandwidth, linearity and stray light of reference radiometers and spectroradiometers of partners and selected end-users.

Monitoring devices using LEDs were developed in the EMRP JRPs ENV03 solarUV and ENV59 ATMOZ to verify and recalibrate the spectral responsivity of radiometers. This expertise was used to develop a LED based source connected to an integrating sphere covering the extended wavelength range from 340 nm to 1700 nm of the discrete wavelength channels of the narrowband filter radiometers with long-term stabilities of 0.1 % per year.

A narrowband tuneable portable radiation source (TuPS 2) was developed which covers the extended wavelength range from 300 nm to 1700 nm for characterising the relative spectral bandpass of each wavelength channel of the network radiometers. This device was successfully tested on CIMEL CE318 radiometers to determine the spectral bandpass of the radiometer channels.

The top of the atmosphere solar spectrum TSIS-1 HSRS was validated with traceable ground-based solar irradiance measurerments to provide a reference solar spectrum over the range from 300 nm to 1700 nm with uncertainties less than 1%. The uncertainty of 1 % of this top of the atmosphere solar spectrum allows the derivation of aerosol properties.

Similarly, lunar phase models ROLO and RIMO were compared to ground-based measuerments to provide a validation of these lunar phase models to allow the retrieval of nighttime AOD with ucnertaintoies approaching those from daytime retrievals.

The project extended the existing GRASP inversion model to provide estimates of the uncertainties for all parameters retrieved with this model, i.e. aerosol size distribution, refractive index, etc.

Results

Development of calibration methods and traceable devices for SI-traceable laboratory and in-field calibrations for solar and lunar radiometers (objective 1)

The laboratory infrastructure using tuneable radiation sources was upgraded at NMI laboratories to accept the sunphotometers of the project. The collaboration with the company manufacturing the CE318 sunphotometer used in the AERONET was crucial in order to interface the radiometers with the laboratory infrastructure. For this, a new firmware was developed for the CE318 sunphotometer in order to control the instrument during the laboratory measurements.

The spectral irradiance responsivities of 3 CIMEL CE318 sunphotometers, 2 PMOD Precision filter radiometers (PFR), and 2 Prede POM sunphotometers were characterised, with uncertainties reaching the desired uncertainty level of 1 % or better for most of them. In addition, the CE318 and POM radiometers were also characterised in spectral radiance responsivities. The field of view of all radiometers, including 3 additional CE318s from collaborator NASA, was characterised on two dedicated setups and used to retrieve the solid view angle from these measurements.

The spectral responsivity of a Precision Solar spectroradiometer (PSR) of SFI DAVOS was characterised at SFI DAVOS and subsequently at PTB, the spectroradiometers BTS VIS/NIR and BTS-IR from collaborator Gigahertz Optik GmbH were characterised and calibrated at PTB, while the radiometer from collaborator EKO-Europe was characterised and calibrated by VSL.

The portable tunable source (TuPS) was developed and characterised at CMI, before being deployed for a field validation campaign at SFI DAVOS. The spectral transmission of several channels of a CIMEL CE318 sunphotometer was measured and compared to previous measurements performed on the same instrument at PTB, showing an excellent agreement, and thus validating this device as a portable spectral characterisation source.

The integrating sphere, coupled with a novel LED-based source was developed and put into operation at PTB. The choice of LEDs was optimised to produce sufficient radiance at the spectral channels of the sunphotometers.

This objective was successfully achieved.

Validation of methods for zero airmass extrapolation by means of traceable ground-based solar spectral irradiance measurements and comparison to satellite-based solar extra-terrestrial spectra (objective 2)

The field campaign was held at the Izaña Atmospheric Observatory (IZO) located on the island of Tenerife (Canary Island, Spain, 28.309 N, 16.499 W) from 6 to 22 September 2022. IZO is a high mountain station at an elevation of 2373 m above sea level (a.s.l) above a strong subtropical temperature inversion layer, which acts as a natural barrier for local pollution and low-level clouds. The site is a primary calibration site for instruments performing zero airmass extrapolations due to its stable atmospheric conditions during most of the year. Based on a long-term climatology of the site, the period of the campaign was selected so as to offer the highest probability for clear skies, stable total column ozone values and a minor probability of Saharan dust intrusions. The campaign employed many instruments from the consortium. The main outcome of the campaign was the determination of top of the atmosphere (ToA) solar spectra from ground based spectral solar irradiance measurements using zero airmass extrapolation techniques. The retrieved ToA agreed to within 1 % with the TSIS-1 HSRS solar spectrum measured from space, while in the ultraviolet region (308 nm to 400 nm), it was possible to reduce the relative uncertainties of this solar spectrum from 1.3 % to 0.8 %, based on the spectral solar irradiance measurements performed during this campaign.

This objective was successfully achieved.

Development of a comprehensive uncertainty budget for aerosol optical properties retrieved from remote sensing-based measurements of direct and scattered solar radiation (objective 3)

Detailed uncertainty budgets for Aerosol Optical Depth were compiled for the three main sunphotometer types operating in three global networks (GAWPFR, AERONET and SKYNET). The resulting report has been made publicly available through the open access repository Zenodo.

The retrieval of additional optical properties of aerosols, such as single scatter albedo, aerosol size distributions, and refractive indices, was obtained using the inversion model GRASP. A comprehensive uncertainty treatment of these properties was developed and implemented in the inversion model. A peer-reviewed paper on the uncertainty treatment by the GRASP model was published and a PhD thesis on the GRASP uncertainty treatment using correlated quantities was successfully defended in April 2022.

A paper on an estimation on the impact of aerosol uncertainties on the radiative forcing of aerosols was published in an open access journal. A detailed dataset used to produce the results discussed in the paper was submitted to Zenodo as a service to the scientific community.

This objective was successfully achieved.

Impact

The winter school SORBETTO-3 was held from 6 to 10 February 2023 at the ESA ESRIN site in Frascati, Italy. Contributions in the form of oral presentations were given by 8 MAPP partners. 30 participants were selected from the submitted applications.

7 peer-reviewed publications on different aspects of MAPP have been published and 7 more were submitted to peer-reviewed journals and are currently under review. MAPP related activities were disseminated through 16 presentations at standardisation & regulatory body meetings and 31 presentations at conferences and workshops.

Three private companies manufacturing sunphotometers and spectroradiometers for measuring solar radiation have joined the project as collaborators. Presentations describing the objectives of the project were given at steering committee meetings of ACTRIS in order to highlight the benefits that the project will bring to the aerosol remote sensing community in Europe. Two new collaborators have joined the project, increasing significantly the end-user up-take and stakeholder involvement (NASA, hosting the global AERONET network, and ESA participating at the field campaign at Izana in September 2022 for the lunar measurements). The collaborators were actively participating in the project and benefitting from the calibration procedure developed within the project.

Training was performed by the project partners on laboratory calibrations and solar measurements. A guest researcher from SFI DAVOS completed a one-month training at PTB in November 2021, focused on the characterisation and calibration of solar and lunar filter radiometers and one spectroradiometer. A training workshop for partners and project collaborators was held during the third project meeting at PTB.

Impact on industrial and other user communities

Industry has benefitted from the developments in novel radiometric technologies developed in this project, which are specifically aimed at promoting the use of emerging technologies for outdoor measurements of solar spectral irradiances covering the UV to near-infrared spectrum. The improved data analysis products and uncertainty estimates developed in this project have an impact on European small and medium-sized enterprises such as GRASP, which are now providing enhanced services tailored to the needs of their customers.

The users of network data such as climate scientists benefit from the comprehensive uncertainty analysis as they will utilise not only the aerosol measurement data but also an objective assessment of the reliability of each data point, which is crucial for producing reliable climate assessments and long-term trend analyses. Furthermore, as these data serve as fiducial reference for various satellite platforms and satellite dissemination platforms, their traceability and reliability have substantially enhanced their importance and usefulness. As an example, recent (Sentinel 5P) and planned (Sentinel 5, EarthCare) missions of the European Space Agency will benefit from these results.

This project supports many users involved with the European Research Infrastructure for the observation of Aerosols, Clouds and Trace gases (ACTRIS) by providing new traceability routes and therefore improved products and services.

Impact on the metrology and scientific communities

The NMIs and DIs have extended their services and collaboration with the scientific community by offering not only access to their laboratory infrastructure as in-kind contribution through the project MAPP, but also by providing essential capacity development and collective activities aimed at creating a common decentralised European platform for radiometric calibrations of atmospheric remote sensing instruments, which is the aim of the European Metrology Network for Climate and Ocean Observation. Specifically, the new procedures developed for radiance and irradiance calibrations of the network instruments have taken into account specific user community needs (wide temperature range, irradiance and radiance level changes over several orders of magnitude) which are usually not offered by metrological institutes, thereby enlarging their portfolio and developing new capabilities to serve the end user needs.

The project has standardised measurements of atmospheric aerosol optical properties from sunphotometers and solar spectroradiometers by establishing and validating consistent calibration and characterisation schemes, based on a mix of outdoor and laboratory-based calibration procedures. The project developed the initial tools and methods in synergy with the end-user laboratories of each aerosol monitoring network and established long-term collaborations needed to effectively implement these new techniques in a routine network calibration routine. The mid to long-term strategy is to support a ground-breaking change in the way calibrations will be performed and to transfer best laboratory practices from the metrological community to the end-user laboratories.

Impact on relevant standards

The project participated in ACTRIS steering meetings and in particular CARS (ACTRIS Centre for Aerosol Remote Sensing) which are responsible for the calibration of radiometers of the European Branch of AERONET. The MAPP results were discussed at these meetings and will feed into a new traceability scheme for the ACTRIS/AERONET network which is under discussion.

Similarly, the Scientific Advisory Group on Aerosols, as well as the Expert Team of Atmospheric Composition Measurement Quality (ET ACMQ) were regularly informed of the progress of MAPP. Possible modifications to the Aerosol Chapter of the former CIMO Guide to Instruments and Methods of Observations to include the new developments of MAPP will be discussed for the next revision lifecyle of this document.

The outputs of this project play a major role in revising existing and setting new standards for the aerosol column-averaged and aerosol remote-sensing components of the Earth Observation community at large. While these changes will occur in a mid-term perspective (5-10 years), their impact will be significant on demonstrating traceability of aerosol remote sensing at a global scale.

Longer-term economic, social and environmental impacts

Some of the major results of this project are advanced calibration services, upgraded data analysis tools, and novel measurement instruments. Several European small and medium-sized businesses were involved in these activities, which thereby have gained a competitive advantage in this specialised global market.

The project has provided a framework for assessing the radiative impact of one of the most uncertain and variable drivers of the climate system through improved measurements and associated modelling. This will support societies in adapting to a changing climate and choosing climate mitigation strategies. Choosing the most effective climate mitigation strategy provides the best long-term benefits to citizens at a minimum cost.

Various geoengineering proposals and ideas aiming to reduce the direct radiative forcing (e.g. through injecting sulphate aerosols in the stratosphere) have been proposed in the past decade, based on the rationale that even aggressive reductions in net emissions of greenhouse gases will be insufficient to limit global climate risks. The success of such proposals depends on the proposed amount of solar dimming that is directly proportional to the aerosol load in the atmosphere. Thus, measurement accuracy of columnar aerosol properties is the key factor to address if such model-based scenarios could be considered realistic. The project results support these investigations, as aerosol measurement uncertainty will be a crucial factor in evaluating issues such the aerosol lifespan, regional aerosol concentration distribution, aerosol transport and others.

In addition, the project will have a long-term impact on public awareness bodies and private and public sectors that are dealing with a number of issues related to health; indirect effects such as aerosol related health effects (additional lower atmosphere aerosol pollution), ozone depletion and UV radiation changes, regional warming and effects on the hydrologic cycle and regional weather changes.

List of publications

1. *Angular responsivity of ground and space-based direct solar irradiance radiometers.* Hülsen, G., Gröbner, J., Pfiffner, D., Gyo, M., Kouremeti, N. and Föller, J. 2022 Journal of Physics: Conference Series. 2149 012001. https://doi.org/10.1088/1742-6596/2149/1/012001

2. *Stray-Light Correction Methodology for the Precision Solar Spectroradiometer.* Kouremeti, N., Gröbner, J. and Nevas, S. 2022 Journal of Physics: Conference Series. 2149 012002. https://doi.org/10.1088/1742-6596/2149/1/012002

3. *A Comprehensive Description of Multi-Term LSM for Applying Multiple a Priori Constraints in Problems of Atmospheric Remote Sensing: GRASP Algorithm, Concept, and Applications.* Dubovik, O., Fuertes, D., Litvinov, P., Lopatin, A., Lapyonok, T., Doubovik, I., Xu, F., Ducos, F., Chen, C., Torres, B., Derimian, Y., Li, L., Herreras-Giralda, M., Herrera, M., Karol, Y., Matar, C., Schuster, G.L., Espinosa, R., Puthukkudy, A., Li, Z. (PTB), Fischer, J., Preusker, R., Cuesta, J., Kreuter, A., Cede, A., Aspetsberger, M., Marth, D., Bindreiter, L., Hangler, A., Lanzinger, V., Holter, C. and Federspiel, C. Frontiers in remote sensing. October 2021. https://doi.org/10.3389/frsen.2021.706851
4. *SI-traceable solar irradiance measurements for aerosol optical depth retrieval.* Kouremeti, N., Nevas, S., Kazadzis, S., Gröbner, J., Schneider, P., and K. M. Schwind, Metrologia 59, 044001, 2022. https://doi.org/10.1088/1681-7575/ac6cbb
5. *Evaluating the effects of columnar NO_2 on the accuracy of aerosol optical properties retrievals.* Drosoglou, T., Raptis, I.-P., Valeri, M., Casadio, S., Barnaba, F., Herreras-Giralda, M., Lopatin, A., Dubovik, O., Brizzi, G., Niro, F., Campanelli, M., and Kazadzis, S., Atmos. Meas. Tech., 16, 2989–3014, 2023. https://doi.org/10.5194/amt-16-2989-2023
6. *Estimates of remote sensing retrieval errors by the GRASP algorithm: application to ground-based observations, concept and validation.* Herrera, M. E., Dubovik, O., Torres, B., Lapyonok, T., Fuertes, D., Lopatin, A., Litvinov, P., Chen, C., Benavent-Oltra, J. A., Bali, J. L., and Ristori, P. R., Atmos. Meas. Tech., 15, 6075–6126, 2022. https://doi.org/10.5194/amt-15-6075-2022
7. *Sensitivity of aerosol optical depth trends using long-term measurements of different sun photometers.* Karanikolas, A., Kouremeti, N., Gröbner, J., Egli, L., and Kazadzis, S., Atmos. Meas. Tech., 15, 5667–5680, 2022. https://doi.org/10.5194/amt-15-5667-2022

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

Project start date and duration:	1 June 2020, 36 months	
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Internal Funded Partners: 1. SFI Davos, Switzerland 2. Aalto, Finland 3. CMI, Czechia 4. NPL, United Kingdom 5. PTB, Germany 6. VSL, Netherlands	External Funded Partners: 7. AEMET, Spain 8. CNR, Italy 9. CNRS, France 10. GRASP SAS, France 11. UoR, United Kingdom 12. UV, Spain 13. UVa, Spain	Unfunded Partners: -
Linked Third Parties: 14. ULILLE, France (linked to CNRS)		
RMG: -		