HARMONIA
International network for harmonization of atmospheric aerosol retrievals from ground based photometers

HARMONIA CA21119

Deliverable 1.1

Create a list of existing and foreseen campaigns or experiments needed for night and day aerosol measurements and report on the data collection and analysis of the data/measurements

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1. Introduction

Aerosols define all particles (solid or liquid) in suspension in the air, except the water droplets or ice crystals of the clouds. Aerosols can be organic (soot, forest fires particles, …), mineral (desert dust, volcanic ashes, …), or have complex chemistry composition (secondary aerosols close to industrial emissions and cities). Some have anthropogenic origin (soot, industrial aerosols, …), others are purely natural (desert dust, sea salt, …).

Aerosols have an influence on public health, with the danger of fine particles on live organisms (Arfin et al., 2023), but also aerosols interact with radiation (solar and thermal infrared radiation) directly (absorbing in the atmosphere, shadowing with scattering back the earth or emitting back to the earth: Li et al., 2022) or indirectly (through interaction with clouds). They definitely have a non-negligible impact on the radiative energy budget of the earth and of the atmosphere, and thus on the climate change, but the quantification of this impact still has some large uncertainties as mentioned in the assessment reports of IPCC (Intergovernmental Panel on Climate Change) as mentioned in the last report: Assessment Report 6 (IPCC, 2023).

A way to reduce these uncertainties is to have a comprehensive knowledge of the "aerosol plumes life": Their offspring, their spatio-temporal dynamics, their ageing, their suspension lifetime and their sources. One way to get this comprehensive knowledge is to have a global widespread ground-based measurement network that measures with high temporal resolution some aerosol related parameters, completed with a satellite observation system.

It is the topic of COST Action HARMONIA (International network for harmonisation of atmospheric aerosol retrievals from ground-based photometers), to focus on aerosol remote sensing, especially on the measurements with the instruments called "photometers".

Photometers are ground-based instruments focus on a natural source of radiation, e.g., during the day: The sun (sunphotometer), make for some defined spectral wavelength region, a radiative measurement, and extract from it, using the equation of Bouguer-Beer-Lambert, the total optical depth of the atmosphere (columnar integrated extinction of the atmosphere), and in a second step retrieve the aerosol optical depth (AOD) at this given wavelength. During the night, photometers can use the moon (lunar photometer) or one of the stars (stellar photometer) as a source of radiation, to make the radiative measurement and extract the parameter AOD. During the day, sunphotometers measure the sky radiance in directions close to the sun, thus characterise the scattering of radiation due to the aerosols, allowing to extract some more parameters characterising the aerosols like the SSA (Single Scattering Albedo), the phase functions, or some optical parameters (e.g., refractive indexes) of the aerosols. Photometer measurements in networks allow thus to 1) characterise aerosol distribution around the world, and aerosol parameters 2) to validate satellite-based measurements of aerosols and radiation.

Main international photometers networks are AERONET (AErosol RObotic NETwork: Holben et al. 1998, Dubovik et al. 2000, Giles et al. 2019), SKYNET (Takamura and Nakaima 2004, Nakajima et al. 2020) and GAW-PFR (Global Atmosphere Watch - Precision Filter Radiometer: Wehrli et al. 2005, WMO 2005, Kazadzis et al. 2018) having different instrument technologies using different retrieval methods. The main target of COST action HARMONIA is to work on the homogenization and harmonisation of the AOD and aerosol parameters measurements and retrieval techniques. The first challenge of a network of measurements is to have reproducible measurements independently of time, geographical location or instrument serial number. To guarantee this reproducibility of measurements, it is important to define a clear calibration protocol in order to set up all instruments of the networks on a reference set of reference instruments. It is also important to organise some calibration and/or comparison campaigns. These calibration/comparison campaigns are the topic of this deliverable.

A measurement campaign in geoscience is a grouping of instruments and instrument methods or of synergies of instruments. The aim can be to characterise a parameter or a phenomenon (e.g., Saharan dust aerosol plumes of the Mediterranean Sea), it can also be a campaign to validate the instrumentation. In this case, it is a calibration and/or comparison campaign. As compared to long-term measurements, provided routinely by the operational networks, campaigns span for a typically short or in any case defined period of time, and are focused on more specific objectives related to instrument comparison and/or open scientific questions that need to be tackled from a multi-instrumental approach.

Calibration and/or comparison campaigns of photometers is the topic of this deliverable: The aim of working groups (WG) 1 and 2 of HARMONIA is to investigate possible improvements of aerosol measurements using photometers. Therefore, WG1 and WG2 organised a census of what existing datasets of campaigns or experiments done in the recent past (2014 - current).

This census, named "list of existing and foreseen campaigns or experiments needed for night and day aerosol measurements and report on the data collection and analysis of the data/measurements" is presented in this deliverable, and we will propose a graphic and tabular analysis of it. Precise information has been gathered by this census, and we gave importance in the way to sort this information: measurements and aerosol retrievals, including main photometry networks and low-cost sensors and other independent instruments databases, are treated separately because of the very different quality of these measurements. Campaigns involving a large number of photometers are treated separately from smaller dimension experiences.

WG1 and WG2 focused their activity in the beginning of HARMONIA in establishing a list of 24 campaigns and experiments, analysing with tables and graphics the exploitable content of these 24 campaigns based on "what kind of instruments are involved", "what kind of measurement have been done / which parameters have been measured", selecting, analysing more deeply a set of the six main campaigns of the last six years, and presenting them in HARMONIA internally and in an international conference and for some of them in publications or reports. Results on these preliminary overviews are shown in the following sections.

2. HARMONIA Campaigns overview

The current status of aerosol observations was described by two lists: the first one collected campaigns and long term-measurements where WG members attended or have contact for data access. The Campaigns must have at least one photometer (sun, moon, or star) or a Sky camera co-located. The availability of ancillary measurements, meaning laboratory analysis or models use, was also asked.

2.1 Campaigns information asked, criteria of acceptance

2.1.1 Google-sheet, information asked:

The HARMONIA members were asked to register their campaigns or experiments they have organized/hosted/participated in. The information collected is listed in Figure 1.

The HARMONIA members filled this information in a google sheet. This google sheet is named “COST-HARMONIA Deliverable D1.1: List of existing campaigns // Stand October 2023” and is available in viewer modus, the link is given in Appendix A1: “List of existing campaigns” in the appendices of this deliverable.

A part of this googlesheet has been summarised in the Annex Table T2 and Annex Table T3 and we can call it “List of existing campaigns” what is the main exigence of this deliverable. 24 field campaigns were recorded in the census; some more are supposed to be collected during the next years of HARMONIA.

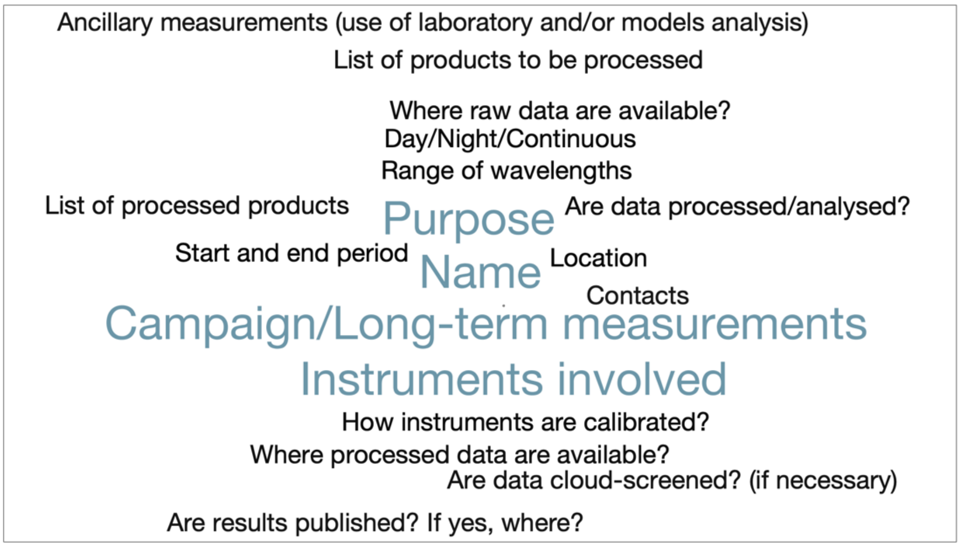


Figure 1: List of information collected in google sheet.

Annex Table T2 summarizes the campaigns dates and locations, and the instruments that have been involved in each campaign. Annex Table T3 is focused on the campaigns’ dataset: Which parameters have been measured in each campaign, who are the contact persons, which institution hosts the data or is competent to help for data exploitation.

2.1.2 Criteria for being considered as a HARMONIA campaign:

The criteria for a campaign/experiment to be accepted in the list are:

- Campaigns where WG member attended or have contact for data access
- The Campaigns must have at least one photometer (sun, lunar or star) or Sky camera) co-located (ground-based aerosol retrievals from sun photometers).
- Not only Campaigns, but also long-term measurements are accepted
- Ancillary measurements (laboratory and model user) can be listed

2.1.3 Map of the campaigns and measurements

Based on the information given in the "List of the campaigns", we present in Figure 2 a map of the locations of the 24 campaigns that are widespread on 20 different sites. The sites of the campaigns are marked with a red triangle. Out of the 24 selected campaigns, there are six specially selected campaigns (because of their duration, the number of instruments and HARMONIA partners involved and the scientific benefits for HARMONIA). The five locations of these six selected campaigns are marked with a yellow circle on the map in Figure 2.

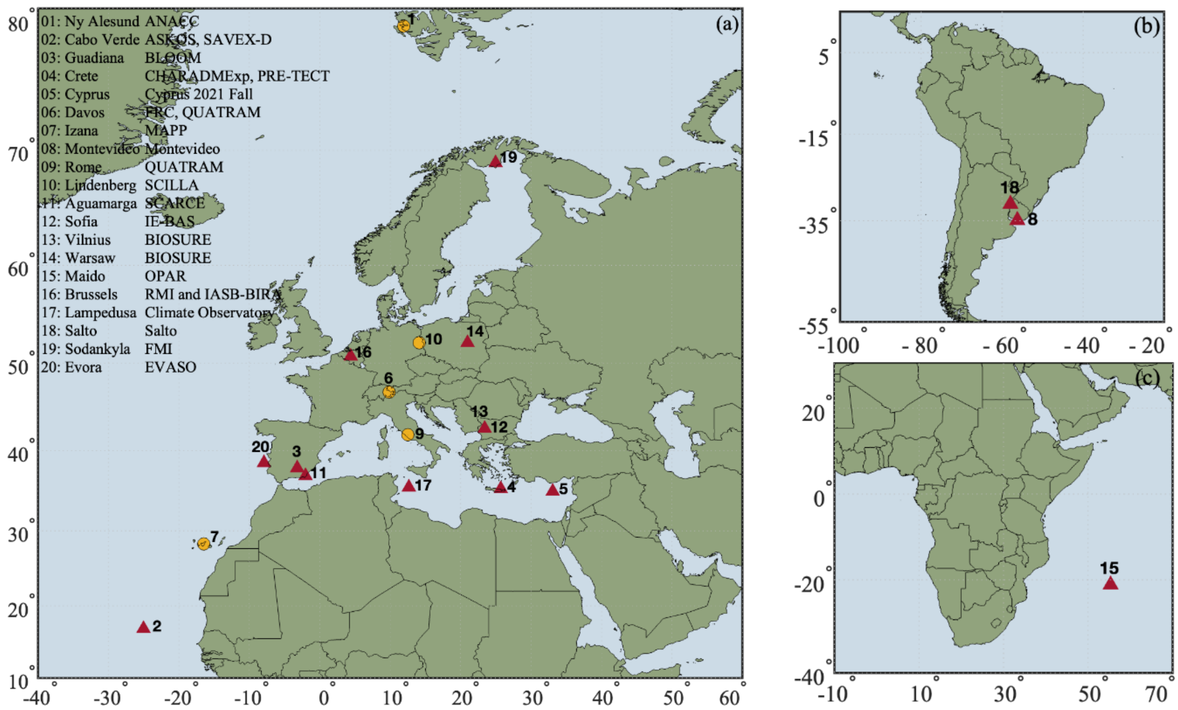


Figure 2: Map of the campaigns and/or long-term measurements. Red triangles: All campaigns and/or long-term measurements, yellow circles: Selected campaigns.

An overview of these special selected campaigns is presented in a pdf document that is linked in Appendix A2: "Special selected campaigns: Overview - Intern HARMONIA presentation", in the appendices of this deliverable. Also, a presentation of the learnings of these selected campaigns for HARMONIA has been presented by Lionel Doppler at EMS (European Meteorological Society) conference in Bratislava (September 2023): Doppler et al. 2023. This presentation is also available in .pdf and linked in Appendix A3: "Doppler et al. 2023 - Learnings from selected campaigns - EMS 2023 Presentation" in the appendices of this deliverable.

3. Overview of campaigns and measurements

3.1 List of instruments, timeline and type of measurements

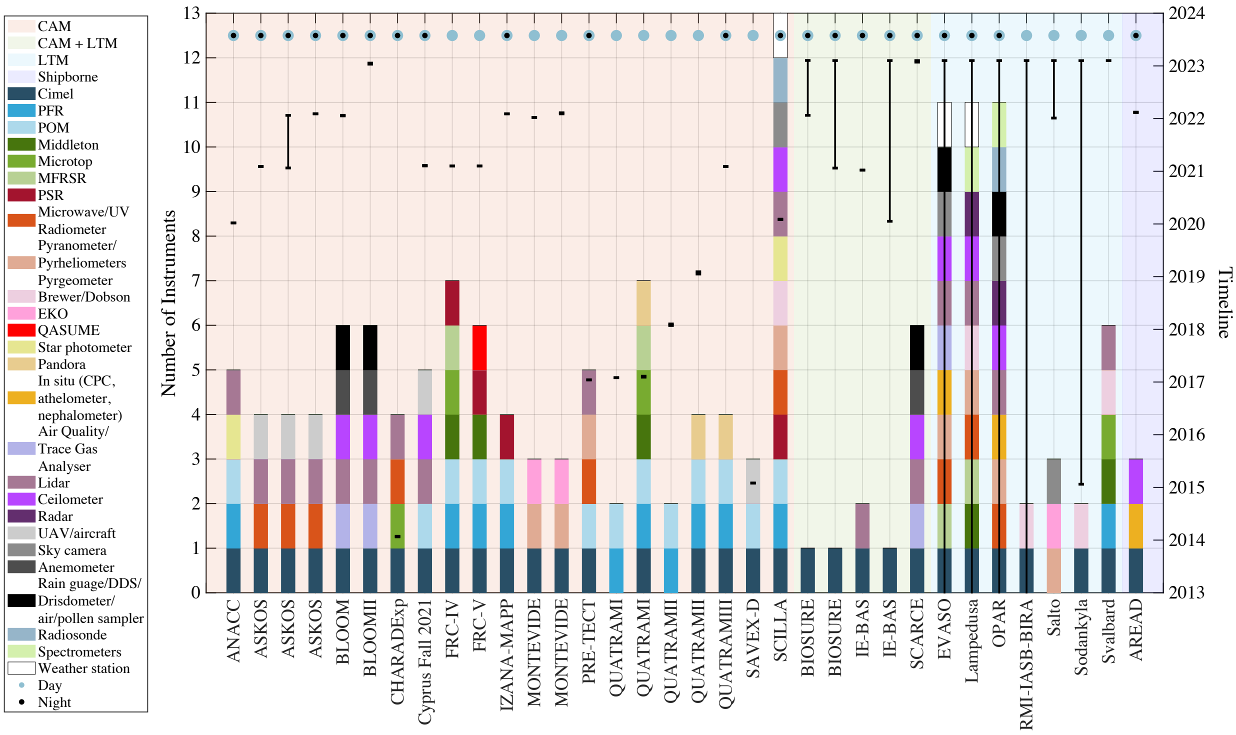


Figure 3: Overview of campaigns (CAM) and long-term measurements (LTM). PFR: Precision Filter Radiometer, PSR: Precision solar SpectroRadiometer, MFRSR: Multi-Filter Rotating Shadowband Radiometer, UAV: Unmanned Aerial Vehicle.

Figure 3 presents a brief description about the campaigns, long-term measurements as well as one ship-borne measurement, instruments used, timeframe of the event and whether the measurements were day, night or continuous. There are 21 campaigns, 5 campaigns with long-term measurements, 7 long-term measurements whose location has been provided in Figure 2 and one ship-borne measurement (AREAD) which was from Spain to Abu Dhabi. The day and/or night measurements comprised of different instruments such as sun/sky/star photometers, Microwave/UV radiometers, broadband shortwave and longwave radiation measuring instruments, spectrometers, in situ devices, trace gas, air quality and vertical profile measuring instruments, sky camera and weather station (more information can be found in Annex Table T2). Focused analysis on selected campaigns is provided in Section 4.

3.2 Information about dataset, access and publication

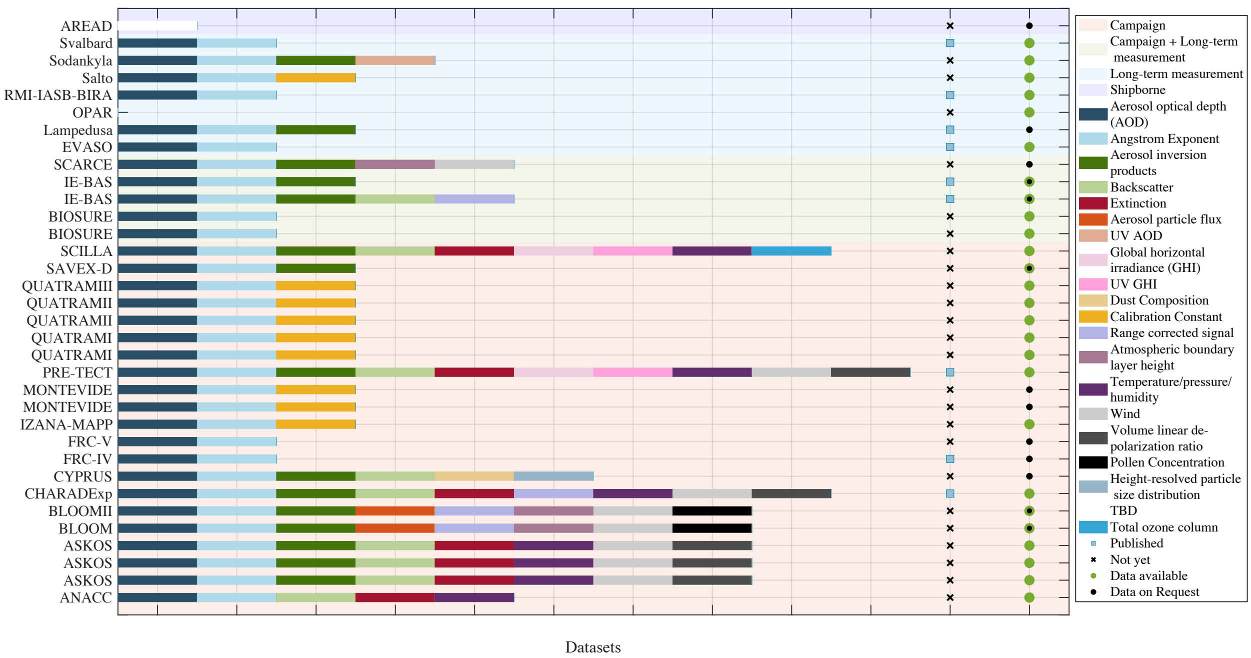


Figure 4: Description of datasets (parameters are colour bars) and data availability (colour markers in the right part of the plot) for each campaign (y axis on the left of the plot).

Figure 4 presents the information about the datasets available from the campaigns and/or long-term measurements, publication status of the results and data availability. More details about the specific datasets, data availability data centres or network websites and contact personnels can be found in Annex Table T3. Out of the 34 campaigns and long-term measurements, results are published for 9 while the remaining are not yet published or are in processing. Most of the datasets are available through data centres or network websites while others can be obtained on request from the designated contact person.

4. Focus on special selected campaigns

From the 24 selected campaigns of the list "List of existing campaigns", there are six special selected campaigns (because of their duration, the number of instruments and HARMONIA partners involved and the scientific benefits for HARMONIA). An overview of these special selected campaigns is presented in a pdf document that is linked in Appendix A2: "Special selected campaigns: Overview - Intern HARMONIA presentation", in appendices of this deliverable. Also, a presentation of the learnings of these selected campaigns for HARMONIA has been presented by Lionel Doppler at EMS (European Meteorological Society) conference in Bratislava (September 2023): Doppler et al. 2023. This presentation is also available in .pdf and linked in Appendix A3: "Doppler et al. 2023 - Learnings from selected campaigns - EMS 2023 Presentation" in the appendices of this deliverable.

The six special selected campaigns are chronologically:

- Nocturnal AOD (Izaña, Tenerife, June 2017)
- QUATRAM (Rome, Davos 2017-2021)
- ANACC (Ny-Ålesund, Svalbard, February 2020)
- SCILLA (Lindenberg, August-September 2020)
- FRC-V (Davos, September-October 2021)
- MAPP (Izaña, Tenerife, September 2022)

In this section we present an overview of each of these specially selected campaigns. For each campaign we will list which current HARMONIA institutions contributed to the campaign and specify what their contribution was.

This section is illustrated by the presentations of Appendix A2 ("Special selected campaigns: Overview - Intern HARMONIA presentation") and Appendix A3

("Doppler et al. 2023 - Learnings from selected campaigns - EMS 2023 Presentation"), linked in the appendices of this deliverable.

4.1 Nocturnal AOD (Izaña 2017)

Nocturnal AOD Izaña campaign (The first multi-instrument nocturnal AOD intercomparison campaign) took place during the moon cycle of June 2017 at the at the high-mountain Izaña Observatory IARC (Izaña Atmospheric Research Center) of AEMET (Agencia Estatal de Meteorología - Spain meteorological service) in Tenerife (Spain).

This campaign involved 2-min synchronous measurements from two different types of lunar photometers (Cimel CE318-T and lunar Precision Filter Radiometer: Lunar PFR) and one stellar photometer (EXCALIBUR: EXtinction CAmera and LumInance BackgroUnd Register, from University of Granada) with AOD inversions at similar wavelengths as the lunar photometer wavelengths. The model ROLO (Robotic Lunar Observatory: Kieffer and Stone 2005) developed by the USGS (U.S. Geological Survey) was compared with the open-access model RIMO (ROLO Implementation for Moon photometry Observation: Barreto et al. 2019) model for lunar photometers' retrievals. Raw signals and AOD retrieved with RIMO have been compared between the lunar photometers (Cimel and Lunar PFR).

12 European institutions contributed to the campaign, of which eight are today HARMONIA partners. The contribution of these HARMONIA partners is:

- AEMET/IARC (Izaña, Tenerife, Spain) hosted the campaign and provided one sun+moon Cimel photometer, and the Micro-Pulsed Lidar MPL-3.
- University of Valladolid (UVa/GOA, Valladolid, Spain) co-organised the campaign, and provided two sun+moon Cimel photometers.
- University of Granada (Granada, Spain) provided and operated the stellar photometer EXCALIBUR during the campaign.
- PMOD/WRC (Davos, Switzerland) and CNR/ISP (Bologna, Italy) provided the lunar photometer from type PFR, and operated it during the campaign.

– Cimel Electronique (Paris, France) co-operated the sun+moon Cimel photometers during the campaign and is the main manufacturer of the photometers of this campaign (solar-lunar photometer Cimel CE318T).
– University of Lille/LOA (Laboratoire d'Optique Atmosphérique) participated in the campaign and provided two sun-moon Cimel photometers.
– DWD (Lindenberg, Germany) provided one sun-moon Cimel photometer.

<table>
<tr><th colspan="2">Nocturnal AOD campaign at a glance</th></tr>
<tr><td colspan="2">Full name: The first multi-instrument nocturnal aerosol optical depth (AOD) intercomparison campaign</td></tr>
<tr><td>Date: 01-17 June 2017</td><td rowspan="4">Additional instruments for data analysis/inversion/outlook:
TOC: Brewers, Dobson,
PWV: GPS sensors
T, P, humidity: Weather station (ground), radio-soundings (balloons: profiles)
Broadband radiation (G, D, I, A): BSRN station, pyranometers (global and diffuse), pyrheliometers, pyrgeometers</td></tr>
<tr><td>Place: AEMET/IARC (Izaña, Tenerife)</td></tr>
<tr><td>Hosting institution: AEMET/IARC</td></tr>
<tr><td>PIs:
Africa Barreto (AEMET/IARC)
Emilio Cuevas (AEMET/IARC)
Carlos Toledano (UVa)</td></tr>
<tr><td>Instruments of interests:
Lunar photometers: Cimel (6), PFR (1), Pandora (1)
Stellar photometers: EXCALIBUR (1)
Lidar: (1), C-LIDAR (1), All-Sky Camera (1)</td><td>Aim of the campaign:
Intercompare the instruments and procedures currently being used to determine the aerosol optical thickness at night, which mainly use the moon as a reference.</td></tr>
</table>

The dataset of "Nocturnal AOD campaign" is very rich.

– The AOD for lunar photometers has been computed with the new RIMO and former ROLO reference lunar reflectivity model. Results showed rather small differences at Izaña over a 2-month time period covering June and July 2017 (±0.01 in terms of AOD calculated by means of a day/night/day coherence test analysis and ± 2% in terms of lunar irradiance).
– Raw-signal dataset: No evidence of significant differences with the Moon's phase angle was found when comparing raw signals of the six Cimel

photometers involved in this field campaign. The raw signal comparison of the participating lunar photometers (Cimel and LunarPFR) performed at coincident wavelengths showed consistent measurements.

- AOD datasets: AOD differences within their combined uncertainties at 870 nm and 675 nm. Slightly larger AOD deviations were observed at 500 nm, pointing to some unexpected instrumental variations during the measurement period.
- Lunar irradiances retrieved using RIMO for phase angles varying between 0° and 75° (full Moon to near quarter Moon) were compared to the irradiance variations retrieved by Cimel and LunarPFR photometers. The results showed a relative agreement within ± 3.5% between the RIMO model and the photometer-based lunar irradiances.
- The AOD retrieved by performing a Langley-plot calibration each night showed a remarkable agreement (better than 0.01) between the lunar photometers. However, when applying the Lunar-Langley calibration using RIMO, AOD differences of up to 0.015 (0.040 for 500 nm) were found, with differences increasing with the Moon's phase angle. These differences are thought to be partly due to the uncertainties in the irradiance models, as well as instrumental deficiencies yet to be fully understood.
- AOD lunar vs. Stellar dataset: High AOD variability in stellar measurements was detected during the campaign. Nevertheless, the observed AOD differences in the Cimel/stellar comparison were within the expected combined uncertainties of these two photometric techniques. Lunar photometry seems to be a more reliable technique, especially for low aerosol loading conditions.
- Uncertainty dataset: The uncertainty analysis performed with the campaign dataset shows that the combined standard AOD uncertainty in lunar photometry is dependent on the calibration technique (up to 0.014 for Langley-plot with illumination-based correction, 0.012–0.022 for Lunar-Langley calibration, and up to 0.1 for the Sun-Moon Gain Factor method). This analysis also corroborates that the uncertainty of the lunar irradiance model used for AOD calculation is within the 5–10% expected range.

- The campaign dataset gave the opportunity to quantify the important technical difficulties that still existed at this time (2017) when routinely monitoring aerosol optical properties at night-time. The small AOD differences observed between the three types of photometers involved in the campaign are only detectable under pristine sky conditions such as those found in this field campaign.
- An outlook is that longer campaigns (set permanently or for a long time many instruments at the same site) are necessary to understand the observed discrepancies between instruments as well as to provide more conclusive results about the uncertainty involved in the lunar irradiance models.

Publication: Barreto et al. 2019

4.2 QUATRAM I, II, III (Rome, Davos, 2017 - 2021)

The QUATRAM (QUality and TRaceability of Atmospheric aerosol Measurements) campaigns are 3 campaigns from 2017 to 2021 separated in 2 phases per campaign. Each campaign has one phase in Davos hosted by PMOD/WRC (Physical and Meteorological Observatorium Davos and World Radiation Centre) and one in Rome hosted by Sapienza University. The goal of the campaigns is the evaluation of the ILP method (Improved Langley Plot: Campanelli et al. 2004, Campanelli et al. 2007) method. ILP is an on-site method for calibration (calculation of the extra-terrestrial direct solar irradiance) of sun and sky radiometers used by the network SKYNET to its sun photometers (Prede-POM). The main product of such instruments and the product that requires this calibration is the AOD. The application of the method requires as inputs measurements of direct solar irradiance and almucantar sky radiance to invert the scattering AOD that is used for the extra-terrestrial constant calculation. The question investigated through the campaign data is how accurate are the ILP calibrations and to which is the effect of the atmospheric conditions to the method's accuracy. Therefore, the campaigns were hosted in 2 locations. One high altitude (station at 1588 m a. s. l.) rural area, Davos, and one low altitude (station at 130 m a. s. l.) urban area (Rome). For the campaign phases in Davos at least one Prede-POM was moved there to be compared with the world reference for AOD measurements: The "PFR Triad": Three instruments of type PFR of PMOD/WRC. PMOD/WRC as a calibration centre hosts a wide range of instruments including a

CIMEL and several PFR sun photometers, 4 brewer and 3 Dobson spectroradiometers that measure TOC (Total Ozone Column) in DU (Dobson Units), and a meteorological station operated by Meteoswiss. For the campaign phases in Rome one PFR was transported to Sapienza University after being calibrated in Davos. Several Prede-POM were installed as well, while the station includes a Cimel sunphotometer.

QUATRAM campaigns at a glance	
QUATRAM: QUality and TRaceability of Atmospheric aerosol Measurements	
QUATRAM-I	
Phase I	Phase II
Date: 09 - 31 August 2017	Date: 22 September – 03 November 2017
Place: Davos	Place: Rome
Hosting institution: PMOD/WRC	Hosting institution: Sapienza university
PIs: Natalia Kouremeti, Stelios Kazadzis	PIs: Monica Campanelli
Instruments of interests: Prede-POM (1) and PFR (1)	Instruments of interests: Prede-POM (4) and PFR (1)
Additional instruments for data analysis/inversion / outlook: Cimel (1), PFR, PSR (2) and PANDORA (1)	Additional instruments for data analysis/inversion / outlook: Cimel (1), Middleton (2), PANDORA (1), MFRSR (2) and Microtops
Aim of the campaign: Evaluation of the ILP (Improved Langley Plot) calibration method	
QUATRAM-II	
Phase I	Phase II
Date: 24 July -19 October 2018	Date: 01 May – 30 September 2019
Place: Davos	Place: Rome
Hosting institution: PMOD/WRC	Hosting institution: Sapienza university
PIs: Natalia Kouremeti, Stelios Kazadzis	PIs: Monica Campanelli
Instruments of interest: Prede-POM (1) and PFR (1)	Instruments of interest: Prede-POM (4) and PFR (1)
Additional instruments for data analysis/inversion / outlook:	Additional instruments for data analysis/inversion / outlook:

Cimel (1), PFR, PSR (2) and PANDORA (1)	Cimel (1), PANDORA (1) and Middleton
Aim of the campaign: Evaluation of the ILP (Improved Langley Plot) calibration method	
QUATRAM-III	
Phase I	Phase II
Date: 03 – 20 September 2021	Date: 07-19 October 2021
Place: Rome	Place: Davos
Hosting institution: Sapienza university	Hosting institution: PMOD/WRC
PI: Monica Campanelli	PI: Natalia Kouremeti and Stelios Kazadzis
Instruments of interests: Prede-POM (2) and PFR (1)	Instruments of interests: Prede-POM (2) and PFR (1)
Additional instruments for data analysis/inversion/outlook: none	Additional instruments for data analysis/inversion/outlook: Cimel (1) and PANDORA (1), PFR and PSR
Aim of the campaign: Evaluation of the ILP (Improved Langley Plot) calibration method	

8 European and international institutions contributed to the campaigns, from which 5 are today HARMONIA partners. The contribution of these HARMONIA partners is:

- CNR/ISAC (Rome, Italy) organised the campaigns, managed the European Prede-POM instruments and developed the ILP and XILP methods, and provided some Prede-POM instruments.
- University of Sapienza (Rome, Italy) hosted the campaign phases of Rome and provided a Cimel and a Prede-POM instrument.
- PMOD/WRC (Davos, Switzerland) hosted the campaigns in Davos, provided and manufactured the PFR instruments.
- University of Valencia (Valencia, Spain) provided Prede-POM instruments and contributed to the development of IPL and XIPL methods and participated in some phases of the campaign.

GRASP (Lille, France) contributed to the analysis of IPL and XIPL methods and participated in some phases of the campaigns.

The QUATRAM datasets provided enough data to compare several Prede-POM instruments with at least 1 PFR and 1 Cimel under different conditions in different locations. Through the measurements we were able to conclude that the Improved Langley Plot method leads to a systematic underestimation of the calibration constant. In Davos the underestimation was 0.7 - 1.6% for 500 nm and 0.2 - 1.8% for 870 nm (the common channels between PFR and Prede-POM) depending on the month. In Rome the underestimation was 2.5 - 3.5% depending on the month and the instrument. All differences in Rome and most in Davos (mainly at 500 nm) result in a lack of compliance with the WMO traceability criteria for AOD. The cause(s) for the worse performance in Rome is under investigation, the results of which are intended for peer-reviewed publication in the near future. An alternative method of SKYNET: the XILP (Cross-Improved Langley Plot) method is also investigated through the data of QUATRAM campaigns. XILP showed improvement compared to ILP (Improved Langley Plot) for Davos campaigns and in most cases for Rome campaigns as well. However, most differences in Rome remained above 1% and some above 2%.

4.3 ANACC (Ny-Ålesund, 2020)

ANACC (Arctic Night Aerosol Characterization Campaign) took place during the last moon cycle of arctic polar night in February 2020. At the polar research village of Ny-Ålesund in Spitsbergen (Svalbard), mainly at AWIPEV (AWI: Alfred-Wegener Institute, IPEV: Institute Paul Emil Victor) station, since German polar institute AWI hosted the campaign.

In ANACC, four photometers were deployed for lunar measurements: two Cimel photometers, one Lunar PFR and one Prede-POM lunar. There are also the permanent instruments of AWIPEV station: the starphotometer and the Raman Lidar KARL. It was therefore planned to make intercomparison between lunar photometers and control if the stellar photometer can help to validate these measurements. The Raman Lidar KARL is intensively used to have information about the vertical profiles of the aerosols, characterise the different layers and make cloud screenings of the photometers data which is particularly difficult with cirrus or PSC (Polar Stratospheric Clouds).

8 European and international institutions contributed to the campaign, from which 6 are today HARMONIA partners. The contribution of these HARMONIA partners is:

- AWI (Potsdam, Germany & Ny-Ålesund, Svalbard) hosted the campaign and provided one Cimel photometer, the stellar photometer and the Raman Lidar KARL.
- University of Valladolid (UVa/GOA, Spain) participated in the campaign, provided one Cimel photometer and the OMEA all-sky camera and contributed to the data inversion for the Cimel photometers.
- AEMET/IARC (Izaña, Tenerife, Spain) and Cimel Electronics (Paris, France) participated in the campaign operating Cimel photometers and Cimel Electronics is the main manufacturer of the photometers of this campaign (solar+lunar photometer Cimel CE318T).

<table>
<tr><th colspan="2">ANACC campaign at a glance</th></tr>
<tr><td colspan="2">ANACC: Arctic Night Aerosol Characterization Campaign</td></tr>
<tr><td>Date: 03-14 February 2020</td><td rowspan="4">Additional instruments for data analysis/inversion/outlook:
Radio Soundings (balloons), broadband radiation, GPS (PWV)</td></tr>
<tr><td>Place: Ny-Ålesund, Spitsbergen (Svalbard)</td></tr>
<tr><td>Hosting institution: AWI (Alfred Wegener Institute, Germany)</td></tr>
<tr><td>PI: Christoph Ritter (AWI), Carlos Toledano (UVa)</td></tr>
<tr><td>Instruments of interests:
Lunar photometers: Cimel (2), PFR (1), Prede-POM (1)
Stellar photometers: Schulz&Partner (1)
Raman Lidar: (1: KARL) / C-LIDAR (1)
All-Sky Camera: OMEA (1)</td><td>Aim of the campaign: Characterization of night-time Polar AOD (technical & scientifically: onset of Arctic Haze season, comparison Cimel - Prede-POM - PFR - Starphotometer), Observation and characterisation of PSC (Polar Stratospheric Clouds) and their optical properties</td></tr>
</table>

PMOD/WRC (Davos, Switzerland) and CNR/ISP (Bologna, Italy) provided the lunar photometer from Type PFR.ANACC dataset is useful for:

- Raw signals: Analysis of operating difficulties in polar very cold conditions. For instance, pointing issues with the robotic tracking instruments (Prede-POM, Cimel)

- AOD dataset lunar: intercomparison between the two Cimel instruments and between the three different types of instruments. Cross-validation
- AOD dataset stellar photometer: Validation of lunar measurements / study of the heterogeneity of the aerosol field. Validation lunar vs. stellar is difficult since the stars used are high or in the opposite direction of the moon, and the moon at the end of the polar night was low and close to the horizon line. Therefore, the potential heterogeneity of the aerosol distribution avoids a secure comparison of lunar vs stellar for cross validation.
- Raman Lidar dataset: Very interesting for cloud screening and aerosol layer structure considering movements of air masses.
- Synergy lunar AOD and spectral variations of AOD characterised with Ångström exponents (AE), stellar AOD and spectral variation and Lidar extinction and backscattering profile: Detection (screening), quantification (COD: Cloud Optical Depth) and characterization (optical properties) of PSC (Polar Stratospheric Clouds)

As outlook HARMONIA partners (having participate in the campaign but other also) can cooperate to finalize the analysis of the campaign dataset (future STSM, VM between partners), or tackle some Harmonia planned task (synergies vertical sounding / columnar measurement: e.g., Lidar/photometers, planned in WG1 and WG2).

4.4 SCILLA (Lindenberg, 2020)

SCILLA (Summer Campaign for Intercomparison of Lunar measurements of Lindenberg's Aerosol) took place during the moon cycle of August & September 2020 at the meteorological observatory MOL-RAO (Meteorological Observatory Lindenberg - Richard Aßmann Observatory) of DWD (Deutscher Wetterdienst: German meteorological service) in Lindenberg (Tauche) in the North-Eastern region of Germany: Brandenburg.

SCILLA deployed a wide instrumentation of photometers during the days (sunphotometers) and nights (lunar photometers, stellar photometers). Regarding aerosol remote sensing, the photometer measurements have been completed by permanent instrumentation of MOL-RAO: Raman, spectral and polarised lidar

RAMSES, ceilometers and COBALD (Compact Optical Backscatter AerosoL Detector: Brabec et al. 2012) aerosol radio sounding carried by balloons (provided by MOL-RAO and Meteoswiss). An OMEA red-green-blue fish-eye all-sky camera was also deployed, provided and managed by GOA (Grupo de Óptica Atmosférica) from UVa (University of Valladolid).

The instrumental suite of MOL-RAO which is a supersite for atmospheric measurements provided all ancillary and complementary parameters (e.g., TOD: Total Ozone Column).

Lunar photometers of all existing types have been deployed: 5 from type Cimel, allowing an "inter-cimel comparison", 1 from type PFR and one from type Prede-POM. Cimel lunar photometers data have been processed with two different lunar reluctance models (ESA/LIME and RIMO). Two starphotometers have been run, and during the days, 8 sunphotometers were measuring the AOD: 5 Cimel instruments, 2 Prede-POM and 1 PFR.

14 European and international institutions contributed to the campaign, from which seven are today HARMONIA partners. The contribution of these HARMONIA partners is:

- DWD (Lindenberg, Germany) hosted the campaign and provided two solar photometers, two sun+moon photometers and one stellar photometer.
- University of Valladolid (UVa/GOA, Valladolid, Spain) provided one sun+moon photometer and the OMEA all-sky camera and contributed to the data inversion of the Cimel sun+moon photometers.
- AEMET/IARC (Izaña, Tenerife, Spain) provided one sun+moon photometer and contributed to the lunar model reflectance comparison.
- Cimel Electronics (Paris, France) provided a sun+moon photometer and is the main manufacturer of the photometers of this campaign (solar+lunar photometer Cimel CE318T).
- PMOD/WRC (Davos, Switzerland) and CNR/ISP (Bologna, Italy) provided the lunar photometer from Type PFR.

University of Granada (Granada, Spain) contributed to the COBALD aerosol profiles inversion and to the scientific support for star photometer analysis.

<table>
<tr><th colspan="2">SCILLA at a glance</th></tr>
<tr><td colspan="2">SCILLA: Summer Campaign for Intercomparison of Lunar measurements of Lindenberg's Aerosol</td></tr>
<tr><td>Date: 25 September – 8 October 2020
Place: Lindenberg (Tauche), Germany
Hosting institution: DWD/MOL-RAO (Deutscher Wetterdienst/Meteorological Observatory Lindenberg - Richard Aßmann Observatory, Germany)
PI: Lionel Doppler (DWD/MOL-RAO)</td><td>Additional instruments for data analysis/inversion/outlook:
TOC: Brewers, Dobson
PWV: GPS sensors, Microwave Radiometer
T, P, humidity: Weather station (ground), 1 balloon radio-sounding every 6 hours (profile)
Broadband radiation (G, D, I, A): BSRN station, pyranometers (global and diffuse), pyrheliometers, pyrgeometers
UV radiation: UV spectrometers (Bentham, BTS)
Spectroradiometers: PSR in direct sun + global</td></tr>
<tr><td>Instruments of interests:
Lunar photometers: Cimel (5), PFR (1), Prede-POM (1)
Stellar photometers: Schulz&Partner (2)
Raman+Spectral+Polar Lidar: (1: RAMSES), Ceilometers (2)
All-Sky Camera: OMEA (1)
COBALD Radiosondes</td><td>Aim of the campaign:
Estimate the instrumental spread between different Cimel lunar photometers, quality check Lunar/Solar, comparison several lunar photometer types, comparison lunar/solar, analysis and comparison columnar measurements (photometers) vs. profile (Lidar, COBALD)</td></tr>
</table>

SCILLA dataset is very rich. There are six good nights of measurements. The possibilities of data inversion are:

- Comparison of all lunar photometers AOD products
- "Inter-cimel comparison": Spread in the AOD product between the 5 lunar photometers from type Cimel
- Comparison lunar vs stellar photometers

– Comparison columnar products (e.g., AOD) to profile products (Lidar, COBALD radiosondes)
– Comparison of different lunar reflectance models for the Cimel lunar photometers' products (ESA/LIME vs. RIMO)
– Analysis instrumental spread day (solar) vs. night (lunar)

All these outlooks are a running cooperation between HARMONIA partners (as well the seven HARMONIA partners involved in the campaign, but also other HARMONIA partners) and can lead to some HARMONIA cooperation (future STSM, VM between partners).

4.5 FRC-V (Davos 2021)

The FRC-V (Fifth WMO Filter Radiometer Comparison) was held from 27 September to 25 October 2021 (29 days) in Davos (46° 49'N, 9° 51'E, at 1590 m above sea level), Switzerland. The objective of the FRC-V campaign was to compare AOD and AE derived from different instruments belonging to different global, regional or national networks, in order to quantify the main factors that are responsible for possible deviations. The aim of the whole activity was to initiate action towards homogenization of the AOD measurements on a global scale. The comparison protocol was formulated according to WMO recommendations. Measurements of each instrument were compared to measurements taken by the WORCC (World Optical Depth Research Calibration Center: Kazadzis et al. 2018) PFR reference triad (hereafter referred to as the "WORCC PFR reference triad"). In total, 31 filter radiometers and spectroradiometers from 12 participating countries participated in this campaign.

8 institutions that are now HARMONIA partners were involved:

– PMOD/WRC (Davos, Switzerland) organised and hosted the campaign, provided 9 PFR (included the reference triad), manufactured all PFR instruments and provided three PSR instruments, one Cimel instrument and QUASUME instruments.
– DWD/MOL-RAO participated in the campaign and provided two PSR, two PFR and one Prede-POM

- AEMET/IARC (Izaña, Tenerife, Spain) and University of Granada (Spain) participated in the campaign and provided Cimel instruments, SMHI (Norrköping, Sweden) participated in the campaign and provided one PFR instrument.

University of Innsbruck (Innsbruck, Austria), University of Valladolid (UVa/GOA, Valladolid, Spain) and University of Lille/LOA, provided Cimel instruments.

<table>
<tr><th colspan="2">FRC-V at a glance</th></tr>
<tr><td colspan="2">FRC-V: Fifth WMO Filter Radiometer Campaign</td></tr>
<tr><td>Date: 27 September - 25 October 2021</td><td rowspan="3">Additional instruments for data analysis/inversion/outlook:
CW sunphotometer (1)</td></tr>
<tr><td>Place: Davos, Switzerland</td></tr>
<tr><td>Hosting institution: PMOD/WRC</td></tr>
<tr><td>PI: Stelios Kazadzis, Natalia Kouremeti</td><td rowspan="2">Aim of the campaign: Objective of the FRC-V campaign was to compare aerosol optical depth and Ångström exponents derived from different instruments belonging to different global, regional or national networks, in order to quantify the main factors that are responsible for possible deviations. The aim of the whole activity was to initiate action towards homogenization of the AOD measurements on a global scale</td></tr>
<tr><td>Instruments of interests:
Sun photometers: PFR (13), Cimel (4), Prede-POM (2), Middleton (1)
Spectroradiometer: PSR (5), QUASUME (2)</td></tr>
</table>

The participating instruments included:

(i) 13 PFR instruments used in the GAW-PFR AOD network which are classic sun photometers measuring at 4 wavelengths with a field of view of ± 1.25°, is equipped with 3 nm to 5 nm bandwidth interference filters and the detector unit is held at a constant temperature of 20° C by an active Peltier system.

(ii) 4 CIMEL sun and sky-scanning radiometers used by AERONET network measuring at eight channels sequentially within a few seconds with a narrow field of view of 1.2°.

(iii) 2 direct sun-pointing Prede-POM-2 sky radiometers used by SKYNET network.

(iv) 1 Carter-Scott SP02 type radiometer (Mitchell and Forgan, 2003), which is similar to the PFR, but has a wider field of view of ± 2.5° with no temperature controlling system.

(v) 1 sun and sky filter radiometer (CW193) belonging to CARSNET (China Aerosol Remote Sensing Network: Che et al., 2019) measuring at 9 channels sequentially from 340 nm up to 1 640 nm (Zheng et al., 2022) ROLO.

(vi) 5 PSR (Precision solar Spectroradiometer: Gröbner and Kouremeti, 2019) which can measure the spectrum from 320 nm up to 1030 nm, with a variable step of an average value of 0.7 nm.

(vii) 2 scanning spectroradiometers QUASUME (Quality Assurance of Spectral Ultraviolet Measurements) which is the European reference for solar ultraviolet (UV) measurements (Gröbner et al., 2005) performed the spectral measurements from 300 nm up to 500 nm (QUASUME) and 550 nm to 1700 nm (IR-QUASUME: newly developed infrared version).

More details about the instruments, network and calibration are provided in Annex Figure F1.

Publication: Kazadzis et al. 2023

4.6 MAPP (Izaña, 2022)

MAPP (Meteorology for Aerosol Optical Properties) campaign of the Metrology for Aerosol Properties (MAPP) project from EURAMET/EMPIR (EURopean Association of national METrology institutes / European Metrology Programme for Innovation And Research) program took place between 03 – 20 September 2022 at the high-mountain Izaña Observatory IARC (Izaña Atmospheric Research Center) of AEMET (Agencia Estatal de Meteorología - Spain meteorological service) in Tenerife (Spain). The aim of the campaign was to use state-of-the-art instruments for intercomparison of spectral and lunar solar irradiance in SI units, AOD and calibration methods for sun and sky radiometers. Applications of the spectral irradiance measurements were to retrieve top-of-the-atmosphere solar irradiance and to improve the model RIMO (ROLO Implementation for Moon photometry Observation: Barreto et al. 2019) from the model ROLO (RObotic Lunar Observatory:

Kieffer and Stone 2005) which is used for retrieving the extra-terrestrial lunar irradiance. Several spectroradiometers with various spectral range and resolution from the near UV to the near IR including the reference QUASUME-UV and QUASUME-IR. There were also instruments from the 3 main networks for AOD retrieval from filter radiometers: GAW-PFR, AERONET and SKYNET and some more instruments including an integrating sphere and a meteorological station. The station of Izaña being at 2373 m a. s. l. and in the subtropical zone offers pristine and dry atmospheric conditions. Due to its proximity to the Sahara Desert, there are also dust episodes making it a very good location for solar and lunar radiation measurements under both very low AOD and humidity conditions, but also higher AOD with large concentration of dust.

<table>
<tr><th colspan="2">MAPP campaign at a glance</th></tr>
<tr><td colspan="2">MAPP: Metrology of Aerosol Optical Properties</td></tr>
<tr><td>Date: 03-20 September 2021</td><td rowspan="4">Additional instruments for data analysis/inversion/outlook:
Pandora (1), Brewer (1), EM27(1), ASD (1), Cimel (1), Integrating Sphere (1)</td></tr>
<tr><td>Place: AEMET/IARC (Izaña, Tenerife)</td></tr>
<tr><td>Hosting institution: AEMET/IARC</td></tr>
<tr><td>PI: Africa Barreto (AEMET/IARC)
co-PIs: Julian Gröbner (PMOD/WRC),
Tom Gardiner & Marc Coleman (NPL)</td></tr>
<tr><td>Instruments of interest:
BTS (3), PSR (1), QUASUME (2), FTIR (3), EKO (2), Prede-POM (1), PFR (1), Cimel (1)</td><td>Aim of the campaign: Top-of-the atmosphere solar and lunar spectral irradiance retrieval, improvement of RIMO/ROLO model, AOD and sun photometer calibration intercomparison and uncertainty budget calculation</td></tr>
</table>

7 European and worldwide institutions contributed to the campaign, from which 6 institutions that are now HARMONIA partners:

- AEMET/IARC (Izaña, Tenerife, Spain) hosted the campaign and provided one sun+moon Cimel photometer, Micro-Pulsed Lidar MPL-3, FTIR and Brewer UV spectrometers.

- PMOD/WRC (Davos, Switzerland) co-organised the campaign and provided UV spectrometer reference QUASUME, PFR and PSR instruments.
- GHO (Gigahertz-Optik, Türkenfeld, Germany), participated in the campaign and provided a BTS UV array spectrometer.
- CNR/ISAC (Rome, Italy) participated in the campaign and provided a Prede-POM instrument.
- University of Lille/LOA (Lille, France) participated in the campaign and provided a Cimel photometer and an integrated sphere.

Physikalisch-Technische Bundesanstalt (PTB) (Braunschweig, Germany) participated in the campaign and provided preliminary laboratory and calibration work for the radiometers.

The MAPP campaign dataset includes a large variety of measurements that can be used for different studies. One study is already published (Gröbner et al. 2023) a summary of which is in section 5.1. This study focuses on the solar spectral irradiance from the spectrophotometers QUASUME (Quality Assurance of Spectral Ultraviolet Measurements), BTS (BiTec Sensor Spektralradiometer, Zuber et al. 2018a, 2018b), PSR (Precision solar Spectroradiometer: Gröbner and Kouremeti 2019) and FTIR (Fourier Transform Infrared Radiometer) including intercomparison of the top-of-the atmosphere radiation with a satellite-based spectrum (TSIS-1 HSRS). A second study is submitted for publication and is focused on an intercomparison of different calibration methods of the SKYNET Prede-POM instruments including 5 calibration methods for extra-terrestrial radiation retrieval and 3 for the solid view angle (SVA).

4.7 General comments and outlook about the whole dataset of all campaigns

Main learnings are:

- From Nocturnal AOD campaign: Working at a pristine Langley Plot site has benefits for calibration, but real conditions are missing for a comprehensive comparison. A good benefit was the quantity of instruments of the same instrument type (in this case: Cimel photometer).

- From QUATRAM: Combining different sites and seasons (polluted, Langley) is definitively a gain for calibration method improvements and evaluation.
- From ANNAC: The synergy of instruments: Lunar photometers / stellar photometer and Lidar proved its efficiency especially in a dynamic heterogeneous atmospheric situation (PSC). The special site conditions (arctic, very cold) were an important hardware test for the instruments and the measurements facilities.
- From SCILLA: The usefulness of having a large quantity of instrument of the same instrument type (Cimel photometers) already noticed in "Nocturnal AOD campaign" has been confirmed. The diversity of instrument types allowed a comprehensive comparison. The method of standardise AOD products (for validation models/calibration), using same inversion method (pressure, ozone, …), allowed an artefact-free comparison of the measurements itself.
- From FRC-V: A long duration and a huge quantity of instruments are procuring benefits for the quality of the comparison. We could point out the lack of AOD retrievals with spectrometers.
- From MAPP: The preliminary laboratory work with spectral calibration of the instruments including the spectrometers showed their benefit. For instance, we observe a real amelioration of spectrometers performances regarding AOD retrievals compared to FRC-V one year earlier (Gröbner et al. 2023).

Recommendations:

A suggested campaign concept would be, after considering the learnings of these six selected campaigns:

- Working with different phases on different sites (urban, standard rural background, and pristine high mountain for Langley-Plot calibration).
- Deploying at least 3 instruments of each type (spread from each type).
- Using synergies with profiling systems like a Lidar, in order to enhance cloud screening.
- Make preliminary laboratory calibration, especially for the spectral systems.

- Develop synergies (star, moon, lidar) to characterise the heterogeneity of the aerosol field and flag the possibility to make some comparisons (lunar vs. stellar for instance).

Outlook:

Some campaigns already have publications (Nocturnal AOD: Barreto et al. 2019, MAPP: Gröbner et al. 2019, FRC-V: Kazadzis et al. 2023). Others have submitted papers (QUATRAM, MAPP). But the datasets of all six selected campaigns are very rich and there is material for studies for interested HARMONIA members. Grants for STSM and VM can be used to support these studies. The studies can be focussed on the campaigns separately or in comparison of the dataset of the different campaigns, searching evolutions of the quality of the measurements and of the retrieval methods and of the models used.

We recommend to focus on studies confronting the instrumental spreads between the campaigns, and the evolution of some quality parameters (AOD retrievals with spectrometers, performance of lunar reflectance models, performance of calibration procedures, …). Also, using photometer products as input of vertical characterization studies (using radiosondes -balloon- or lidars products) are of great benefit.

5. Scientific production and grants about campaigns during Harmonia

5.1 Scientific production

5.1.1 Aerosol optical depth comparison between GAW-PFR and AERONET-Cimel radiometers from long-term (2005–2015) 1 min synchronous measurements

(Cuevas et al., 2019)

This study concerns the traceability of AOD for long-term measurements of a Cimel sun photometer network AERONET (AErosol RObotic NETwork) and a PFR belonging to the network GAW-PFR and the attribution of differences. The instruments were co-located at the station of Izaña, Tenerife (2373 m a. s. l.) and the comparison includes measurements from the period 2005-2015. According to WMO (World

Meteorological Organisation) the 2 instruments are traceable when at least 95% of the AOD differences are within specific limits that are a function of the air mass coefficient. According to this study, the percentage of data within the WMO limits was >92 % at 380 nm, >95 % at 440 nm and 500 nm, and 98 % at 870 nm. It's worth noting that at 380 nm and 440 nm the wavelength difference between the 2 instruments is larger (nominally 12 nm and 28 nm) and at this region the effects of Rayleigh and Mie scattering are larger compared to the other 2 wavelengths. Therefore, they are not directly comparable, and the use of AE is required. An error to AE of 0.5 would result in an error of AOD up to 5% in the case of this study. However, the AE differences were below 0.1 even under AOD >0.03 and AE <1. According to the publication, differences between the 2 networks on removing the effects of Rayleigh scattering, O_3 and NO_2 during the AOD calculation have negligible effect. A non-negligible effect is the different field of view of the instruments when there is significant forward scattering from dust aerosols (concerns AOD>0.1), which partially explains the worse performance at 380 nm since the effect is stronger for shorter wavelengths. The calibration differences can also explain the worse performance at 380 nm. Potential reasons for higher calibration errors at this wavelength are the higher AOD variability at the shorter wavelengths, problems related to filter blocking issues or non-accounted effect of temperature at UV region as Cimel instruments aren't temperature stabilised. The imperfect synchronisation of the instruments, according to the variability of AOD for 1 min, can explain only 0.11% - 2.31% of the observed differences outside the WMO limits depending on the wavelength and the atmospheric conditions. Finally, the effect of cloud screening differences was negligible, but the station of Izaña has very little cloudiness due to its location and the results may differ significantly in different locations.

5.1.2 Sensitivity of aerosol optical depth trends using long-term measurements of different sun photometers

(Karanikolas et al., 2022)

The goal of the study is to assess the differences of AOD long-term measurements and trends between instruments from the networks AERONET using Cimel and GAW-PFR network using the PFR instruments. Also, the study aimed to assess the sensitivity of AOD trends to different factors: measurement uncertainty, temporal resolution, averaging method and trend estimation method. The study includes a

Cimel-PFR AOD comparison and trend analysis for the period 2007 - 2019. The instruments measure at 2 directly comparable wavelengths (500/501 nm and 862/870 nm). More than 95% of their AOD differences were within the accepted limits defined by WMO. The monthly median AOD differences showed a good correlation (coefficient of determination $R^2 > 0.95$) and most of them were within the monthly AOD measurement uncertainties. However, the trend differences for synchronous data equals (500/501 nm) or exceeds (862/870 nm) the calculated trend uncertainties at 1σ (fitting standard error and trend uncertainty due to measurement uncertainty). This shows that the AOD trends can be very sensitive to AOD differences that are conventionally considered to be small. The effect of temporal resolution was smaller than the trend uncertainties (PFR instruments measure every minute, while Cimel instruments have a variable frequency of up to ~15 minutes). Finally, the study includes time-varying trends using dynamic linear modelling. All dynamic linear modelling trend differences were within the uncertainties. However, the trends were not consistent with least-squares linear trends as they were not monotonic. Since trends are not necessarily linear or monotonic, time-varying trends can provide a more objective criterion to identify deviations from linear or monotonic behaviour. The results of this work cannot be generalised to every location and instrument comparison, but they highlight various challenges in estimating AOD trends.

5.1.3 Spectral aerosol optical depth from SI-traceable spectral solar irradiance measurements

(Gröbner et al., 2023)

The goal of the study is to investigate the accuracy of laboratory radiometric calibration to SI units and top-of-the atmosphere solar irradiance using ground based spectroradiometers at a high-altitude location and the effect of the differences on AOD retrieval (Gröbner et al., 2023). Different spectroradiometers were transported to Izaña Tenerife for the MAPP campaign in September 2022 (Section 4.6). The study is focused on the BTS, PSR, FTIR and the reference QUASUME instruments. The direct spectral irradiance measured at Izaña is extrapolated to 0 air mass and compared to the TSIS-1 HSRS satellite based extra-terrestrial spectrum. The QUASUME, calibrated to SI at PTB retrieved extra-terrestrial spectra above 400 nm excluding significant gas absorption bands differ up to 1% with TSIS-1 HSRS (below 400 nm there are mainly below 1% except a few wavelengths getting closer to 2%). For BTS and PSR the differences are larger, but still at most wavelengths without significant gas absorption the differences remain below 1% above 500 nm and below 2% for shorter wavelengths. The AOD calculated from the spectroradiometers at the closest wavelengths to the ones measured by PFR or Cimel (340, 380, 440, 500, 675, 870, 1020 and 1640 nm) showed compliance with WMO traceability criteria in most cases. Cimel and PFR had more than 95% of their AOD differences within the WMO (World Meteorological Organisation) limits for all common wavelengths or close enough to scale the observations to a common wavelength (1640 nm is unsuitable). The reference AOD is considered the PFR for all wavelengths except 1640 nm where the reference is Cimel. The QUASUME instruments had more than 95% of data within the WMO limits against the reference AOD at all wavelengths. BTS satisfied the traceability criteria at all wavelengths except 440 nm. The PSR didn't satisfy the traceability criteria at 675 nm. For all instrument types the average AOD differences remained below 0.01 at all wavelengths. The main conclusion of the study is that the laboratory calibration of spectroradiometers to SI units does not induce large enough uncertainty to prevent AOD retrieval accurate enough according to WMO standards at wavelengths that gas absorption does not significantly increase the AOD uncertainty.

5.1.4 GAW Report about FRC-IV and FRC-V

(Kazadzis et al., 2018a, Kazadzis et al., 2023)

FRC-IV (Fourth WMO Filter Radiometer Comparison) was held from 28 September and 16 October 2015 in Davos, Switzerland. 30 instruments including filter radiometers and spectroradiometers took part from 12 countries including PFR, Cimel, Prede-POM, MFRSR (Multi-Filter Rotating Shadowband Radiometer), PSR (Precision Spectroradiometer), SPO, SSIM and Microtops. The AOD retrieved from these instruments were compared at 368 ± 3 nm, 412 ± 3 nm, 500 ± 3 nm and 865 ± 5 nm to the reference triad based on the WMO criterion (95% of the data has to be within 0.005 ± 0.001/air mass). The number of instruments that achieved the goal of meeting the WMO criterion were found to be 24 (out of 29) at 865 nm and 500 nm, 13 (out of 21) at 412 nm and 12 (out of 17) at 368 nm. The comparison results were found to be the best corresponding to 500 nm followed by 867 nm while lower wavelengths (368 nm and 412 nm) showed comparatively more deviations.

FRC-V (Fifth WMO Filter Radiometer Comparison) was held from 27 September to 25 October 2021 (29 days) in Davos (46.82° N, 9.85° E, 1590 m a. s. l.), Switzerland. The objective of the FRC-V campaign was to compare AOD and AE derived from different instruments belonging to different global, regional, or national networks, to quantify the main factors that are responsible for possible deviations. The aim of the whole activity was to initiate action towards homogenization of the AOD measurements on a global scale. The comparison protocol was formulated according to WMO recommendations. Measurements of each instrument were compared to measurements taken by the WORCC PFR reference triad (hereafter referred to as the "WORCC PFR reference triad"). In total, 31 filter radiometers and spectroradiometers from 12 participating countries participated in this campaign including PFR, Cimel, Prede-POM, SPO, PSR, QUASUME and CW photometer (refer to Annex Figure F1 for more details). The AOD measurements from all the instruments were compared with the WORCC PFR reference triad at six wavelengths namely 368/380 nm, 400/412/440 nm, 500 nm, 675 nm, 862 nm and 1020 nm with the percentage of instruments with 95% agreement within the WMO limits being at least 68%, 82%, 91%, 90%, 100% and 85%, respectively. Furthermore, comparison of AE with the WORCC reference triad showed that 24 out of 29 instruments agreed within ±0.2.

5.2 Overview of grants relative to the campaigns

One VM (Virtual Mobility) has been attributed to a specific campaign work during HARMONIA, this was:

Title: Improving Lunar PFR aerosol optical depth retrievals
Timeline: 25 July – 06 September 2023
Grantee: Natalia Kouremeti (PMOD/WRC)
VM report: The VM report is available in the intern documentation of COST-HARMONIA and has been submitted to COST
Summary of the VM: Improving the lunar based AOD has an impact on various communities. One of those is the aerosol Lidar measuring community where frequently, Raman measurements have to be

performed at night-time and coincidence (lunar based) AOD values are essential for quality assurance but also for various related studies.
The lunar photometer PFR-L002 manufactured at PMOD/WRC is able to provide lunar irradiance measurements with an uncertainty of less than 0.8% (SI calibration at Physikalisch-Technische Bundesanstalt). Within the framework of the MAPP (Metrology for Aerosol optical Properties: MAPP-19ENV04) project, a campaign was organised at Izaña in September 2022. Results showed relative differences in the lunar AOD that were based either on the RIMO (ROLO Implementation for Moon photometry Observation) model or the SI-calibrated sun-photometers.
The work granted with this VM consisted in a two-month (two lunar cycles) lunar-PFR campaign at Rethymno Crete, Greece), in an area with very low probability of cloud presence during summer. The aim of this campaign was to operate the PFR-L002 alongside the PFR sun-photometer and two new lunar PFR instruments and to try to link the lunar AOD and Ångstrøm retrievals to the standard solar based ones. The campaign could not take place at PMOD/WRC (Davos, Switzerland) mainly due to the frequent cloudiness conditions. Rethymno (Crete, Greece) has been selected, apart from the cloudless-skies high probability, for the variety of aerosol types (marine, urban, Saharan dust) observed during the summertime.

6. Outlook and recommendation

6.1 Suggestions about how to exploit the datasets of the campaigns

- Gather ideas and form working groups towards exploiting data from the campaigns towards a specific goal either related with photometer performances or with an atmospheric or climate question.
- The studies can be focussed on the campaigns separately or in comparison of the dataset of the different campaigns, searching evolutions of the quality of the measurements and of the retrieval methods and of the models used.
- We recommend to focus on studies confronting the instrumental spreads between the campaigns, and the evolution of some quality parameters (AOD retrievals with spectrometers, performance of lunar reflectance models, performance of calibration procedures, …).

- Using photometer products as input of vertical characterization studies (using radiosondes -balloon- or lidars products) are of great benefit.

6.2 Suggestion how to design a future campaign

- Inclusion of low-cost sensors
- Assess cloud screening instrument performances
- Separate calibration and post processing sources of uncertainties
- Inclusions of lab measurements for instrument calibration and characterization
- Define goals and chose among short term and long-term comparisons
- Provide overview of different network strategies (e.g., ACTRIS, WMO-GAW, SKYNET, Brewer)
- Increase efforts for UVB and UVA range and infrared measurements
- Satellite data inclusion
- Using different phases at different places (urban, rural background, pristine Langley-Plot site)
- Having a long duration and a large number of instruments of the same type

6.3 Actions planned in Harmonia related to this topic

FRC-VI (Sixth WMO Filter Radiometer Comparison) in 2025 at PMOD/WRC (Davos, Switzerland) could be an experiment linked with Harmonia goals and objectives.

7. Conclusion

This document (Deliverable D1.1. of the COST Action HARMONIA) is a tool that should help HARMONIA members to have knowledge of recent or running photometer calibration/comparison campaigns or experiments, to have information about the datasets and to provide brief analysis of the results and the

potential of these datasets. Meta information about these 24 campaigns and persons to contact (PI, reports or publication authors, institute or person hosting the datasets) for each campaign are listed, so that interested HARMONIA members will, thanks to this deliverable, have no difficulty to access to relevant documentation, information and data of the campaigns.

We are looking forward to facilitating the common work between people and institutions of HARMONIA about these 24 existing/former campaigns and experiments listed in this deliverable, and we encourage all kinds of collaborations and studies. COST action HARMONIA will be glad to support these works with grants (e.g., VM: Virtual Mobility or STSM: Short Term Scientific Mission)

References

Arfin, T., Pillai, A.M., Mathew, N. et al. An overview of atmospheric aerosol and their effects on human health. Environ Sci Pollut Res (2023). https://doi.org/10.1007/s11356-023-29652-w

Barreto, A., Román, R., Cuevas, E., Pérez-Ramírez, D., Berjón, A.J., Kouremeti, N., Kazadzis, S., Gröbner, J., Mazzola, M., Toledano, C. and Benavent-Oltra, J.A. Evaluation of night-time aerosols measurements and lunar irradiance models in the frame of the first multi-instrument nocturnal intercomparison campaign. Atmospheric environment, 202, pp.190-211, 2019.

Brabec, M., Wienhold, F. G., Luo, B. P., Vömel, H., Immler, F., Steiner, P., Hausammann, E., Weers, U., and Peter, T.: Particle backscatter and relative humidity measured across cirrus clouds and comparison with microphysical cirrus modelling, Atmos. Chem. Phys., 12, 9135–9148, doi:10.5194/acp-12-9135-2012, 2012.

Campanelli M., Teruyuki Nakajima, and Bruno Olivieri, "Determination of the solar calibration constant for a sun-sky 717 radiometer: proposal of an in-situ procedure," Appl. Opt. 43, 651-659 (2004) 718-719

Campanelli M., Víctor Estellés, Claudio Tomasi, Teruyuki Nakajima, Vincenzo Malvestuto, and José Antonio Martínez-720 Lozano, "Application of the SKYRAD Improved Langley plot method for the in situ calibration of CIMEL Sun-sky 721 photometers," Appl. Opt. 46, 2688-2702 (2007)

Cuevas, E., Romero-Campos, P. M., Kouremeti, N., Kazadzis, S., Räisänen, P., García, R. D., Barreto, A., Guirado-Fuentes, C., Ramos, R., Toledano, C., Almansa, F., and Gröbner, J.: Aerosol optical depth comparison between GAW-PFR and AERONET-Cimel radiometers from long-term (2005–2015) 1 min synchronous measurements, Atmos. Meas. Tech., 12, 4309–4337, https://doi.org/10.5194/amt-12-4309-2019, 2019.

Doppler, L., Kazadzis, S., Kouremeti, N., Masoom, A., Barreto, A., Cuevas, E., Toledano, C., Roman, R., Campanelli, M., and Ritter, C.: Learnings of measurement campaigns in photometry instrumentation and inversion methods, a COST/HARMONIA study, EMS Annual Meeting 2023, Bratislava, Slovakia, 4–8 Sep 2023, EMS2023-656, https://doi.org/10.5194/ems2023-656, 2023. (This presentation is available in Appendix A3 ("Doppler et al. 2023 - Learnings from selected campaigns - EMS 2023 Presentation") linked in the appendices of this deliverable)

Dubovik, O. and King, M.D., A flexible inversion algorithm for retrieval of aerosol optical properties from Sun and sky radiance measurements. Journal of Geophysical Research: Atmospheres, 105(D16), pp.20673-20696, 2000.

Giles, D. M.; Sinyuk, A.; Sorokin, M. G. et al. Advancements in the Aerosol Robotic Network (AERONET) Version 3 Database – Automated Near-real-time Quality Control Algorithm with Improved Cloud Screening for Sun Photometer Aerosol Optical Depth (AOD) Measurements. Atmospheric Measurement Techniques 2019, 12, 169–209. https://doi.org/10.5194/amt-12-169-2019.

Gröbner, J., Schreder, J., Kazadzis, S., Bais, A. F., Blumthaler, M., Görts, P., Tax, R., Koskela, T., Seckmeyer, G., Webb, A. R., and Rembges, D.: Traveling reference spectroradiometer for routine quality assurance of spectral solar ultraviolet irradiance measurements, Appl. Optics, 44, 5321–5331, 2005.

Gröbner, J.; Kouremeti, N. The Precision Solar Spectroradiometer (PSR) for Direct Solar Irradiance Measurements. Solar Energy 2019, 185, 199–210. https://doi.org/10.1016/j.solener.2019.04.060.

Gröbner, J., Kouremeti, N., Hülsen, G., Zuber, R., Ribnitzky, M., Nevas, S., Sperfeld, P., Schwind, K., Schneider, P., Kazadzis, S., Barreto, Á., Gardiner, T., Mottungan, K., Medland, D., and Coleman, M.: Spectral aerosol optical depth from SI-traceable spectral solar irradiance measurements, Atmos. Meas. Tech., 16, 4667–4680, https://doi.org/10.5194/amt-16-4667-2023, 2023.

Holben, B., Eck, T., Slutsker, I., Tanré, D., Buis, J., Setzer, A., Vermote, E., Reagan, J., Kaufman, Y., Nakajima, T., Lavenu, F., Jankowiak,I., and Smirnov, A.: AERONET—A Federated Instrument Network and Data Archive for Aerosol Characterization, Remote Sensing ofEnvironment, 66, 1 – 16, https://doi.org/https://doi.org/10.1016/S0034-4257(98)00031-5, 1998

Karanikolas, A.; Kouremeti; N., Gröbner, J.; Egli, L. and Kazadzis, S. Sensitivity of aerosol optical depth trends using long-term measurements of different sun photometers. Atmospheric Measurement Techniques 2022, 15, 5667–5680. https://doi.org/10.5194/amt-15-5667-2022.

Kazadzis, S.; Kouremeti, N.; Nyeki, S. et al. The World Optical Depth Research and Calibration Center (WORCC) Quality Assurance and Quality Control of GAW-PFR AOD Measurements. Geoscientific Instrumentation, Methods And Data Systems 2018b, 7 (1), 39–53. https://doi.org/10.5194/gi- 7-39-2018.

Kazadzis, S., Kouremeti, N., Diémoz, H., Gröbner, J., Forgan, B. W., Campanelli, M., Estellés, V., Lantz, K., Michalsky, J., Carlund, T., Cuevas, E., Toledano, C., Becker, R., Nyeki, S., Kosmopoulos, P. G., Tatsiankou, V., Vuilleumier, L., Denn, F. M., Ohkawara, N., Ijima, O., Goloub, P., Raptis, P. I., Milner, M., Behrens, K., Barreto, A., Martucci, G., Hall, E., Wendell, J., Fabbri, B. E., and Wehrli, C.: Results from the Fourth WMO Filter Radiometer Comparison for aerosol optical depth measurements, Atmos. Chem. Phys., 18, 3185–3201, https://doi.org/10.5194/acp-18-3185-2018, 2018a.

Kazadzis, S., Kouremeti, N., Gröbner, J. Fifth WMO Filter Radiometer Comparison (FRC-V), Research Infrastructure Quality Assurance GAW Report No. 280, World Meteorological Organization, 2023. https://library.wmo.int/idurl/4/66263

Kieffer, H.H., Stone, T.C., 2005. The spectral irradiance of the moon. Astron. J. 129, 2887–2901.

IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, 184 pp., doi: 10.59327/IPCC/AR6-9789291691647.

https://www.ipcc.ch/report/ar6/syr/longer-report
https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_SPM.pdf

Li, J., Carlson, B.E., Yung, Y.L. et al. Scattering and absorbing aerosols in the climate system. Nat Rev Earth Environ 3, 363–379 (2022). https://doi.org/10.1038/s43017-022-00296-7

Mitchell, R. M.; Forgan, B. W. Aerosol Measurement in the Australian Outback: Intercomparison of Sun Photometers. Journal of Atmospheric and Oceanic Technology 2003, 20 (1), 54–66. https://doi.org/10.1175/1520-0426(2003)020<0054:AMITAO>2.0.CO;2.

Nakajima, T.; Campanelli, M.; Che, H. et al. An Overview of and Issues with Sky Radiometer Technology and SKYNET. Atmospheric Measurement Techniques 2020, 13, 4195–4218. https://doi.org/10.5194/amt-13-4195-2020.

Takamura, T. and Nakajima, T.: Overview of SKYNET and its activities, Optica Pura y Aplicada, 37, 3303–3308, 2004

Wehrli, C.: GAWPFR: A network of aerosol optical depth observations with precision filter radiometers, GLOBAL ATMOSPHERE WATCH,p. 36, 2005.

WMO: WMO/GAW Experts Workshop on a Global Surface-Based Network for Long Term Observations of Column Aerosol Optical Properties,GAW Report No. 162, WMO TD No. 1287, https://library.wmo.int/pmb_ged/wmo-td_1287.pdf, 2005

Zheng, Y.; Che, H.; Wang, Y. et al. Evaluation of Aerosol Microphysical, Optical and Radiative Properties Measured with a Multiwavelength Photometer. Atmospheric Measurement Techniques 2022, 15 (7), 2139–2158. https://doi.org/10.5194/amt-15-2139-2022.

Zuber, R., Ribnitzky, M., Tobar, M., Lange, K., Kutscher, D., Schrempf, M., Niedzwiedz, A., and Seckmeyer, G.: Global spectral irradiance array spectroradiometer validation according to WMO, Meas. Sci. Technol., 29, 105801, https://doi.org/10.1088/1361-6501/aada34, 2018a.

Zuber, R., Sperfeld, P., Riechelmann, S., Nevas, S., Sildoja, M., and Seckmeyer, G.: Adaption of an array spectroradiometer for total ozone column retrieval using direct solar irradiance measurements in the UV spectral range, Atmos. Meas. Tech., 11, 2477–2484, https://doi.org/10.5194/amt-11-2477-2018, 2018b.

Annex: Tables and Figures

Annex Table T1: Acronyms description

Acronym	Description
AE	Ångström Exponents (α, β): characterise AOD spectral variation
AEMET	Agencia Estatal de Meteorología (Spain meteorological service)
AERONET	AErosol RObotic NETwork: AOD and aerosol properties measurements network using Cimel CE-318 photometer
ANACC	Arctic Night Aerosol Characterization Campaign: Arctic campaign of Ny-Ålesund (Svalbard), February 2020.
AOD	Aerosol Optical Depth (also known as AOT: Aerosol Optical Thickness): Main parameter used to characterise aerosol amount and aerosol impact on radiation in the atmosphere. AOD is also the main parameter measured with photometers.
AWI	Alfred-Wegener-Institut (German Polar Institute)
AWIPEV	AWI and IPEV joint station at Ny-Ålesund, Spitsbergen (Svalbard)
BTS	BiTec Sensor Spektralradiometer: Array spectroradiometer manufactured by GHO
CNR	Consiglio Nazionale delle Ricerche (Italian national research council)
COBALD	Compact Optical Backscatter AerosoL Detector: Radiosounding (balloon carried) sensor for measuring in-situ the aerosol extinction profile.
DWD	Deutscher Wetterdienst (German meteorological service)
EMPIR	European Metrology Programme for Innovation and Research
EURAMET	EURopean Association of national METrology institutes
FRC-IV	Fourth WMO Filter Radiometer Campaign: WMO campaign organised in Davos at PMOD/WRC, September/October 2015
FRC-V	Fifth WMO Filter Radiometer Campaign: WMO campaign organised in Davos at PMOD/WRC, September/October 2021
GAW	Global Atmosphere Watch: WMO Program of trends monitoring of the atmosphere
GAW-PFR	Global Atmosphere Watch - Precision Filter Radiometer network: AOD measurement network of WMO/GAW Program
GHO	Gigahertz-Optik, instrument manufacturer based in Türkenfeld, Germany
GOA	Grupo de Óptica Atmosférica, UVa (Valladolid, Spain)
GRASP	Generalized Retrieval of Atmosphere and Surface Properties: Company based in Lille, France

HARMONIA	International network for harmonisation of atmospheric aerosol retrievals from ground-based photometers: Name of the COST action
IARC	Izaña Atmospheric Research Center: AEMET observatory at Izaña (Tenerife)
IASC	Institute of Atmospheric Sciences and Climate: CNR institution based in Rome (Italy)
IPEV	Institut Paul Émile Victor (French Polar Institute)
IPCC	Intergovernmental Panel on Climate Change
ISP	Istituto di Scienze Polari (institute of polar science), CNR institution based in Bologna, Italy
LIDAR	LIght Detection And Ranging
LOA	Laboratoire d'Optique Atmosphérique: institute of University of Lille, France
MAPP	Metrology of Aerosol Optical Properties: EURAMET/EMPIR project campaign at Izaña (Tenerife, Spain), September 2022
MFRSR	Multi-Filter Rotating Shadowband Radiometer
MOL-RAO	Meteorological Observatory Lindenberg - Richard Aßmann Observatory: DWD observatory of Lindenberg (Tauche, Germany)
PFR	Precision FilterRadiometer: Photometer manufactured by PMOD/WRC
PI	Principal Investigator
PMOD/WRC	Physikalisch-Meteorologisches Observatorium Davos and World Radiation Center
POM	Precise design Of Meteorological and scientific instrument: Photometer manufactured by Prede and used in the network SKYNET.
PSR	Precision Solar SpectroRadiometer: Spectroradiometer manufactured by PMOD/WRC
PSC	Polar Stratospheric Clouds
PTB	Physikalisch-Technische Bundesanstalt, German institute of metrology based in Braunschweig (Brunswick)
PWV	Precipitable Water Vapour: Columnar integrated amount of Water Vapour (in mm)
QUASUME	Quality Assurance of Spectral Ultraviolet Measurements: Spectrometer reference system of PMOD/WRC in Davos
QUATRAM	QUality and TRaceability of Atmospheric aerosol Measurements: 3 campaigns (QUATRAM I, II and III) of two phases (Rome and Davos), 2017-2021
RIMO	ROLO Implementation for Moon photometry Observation: open lunar reflectance model developed by GOA and AEMET/IARC
ROLO	Robotic Lunar Observatory: lunar reflectance model of USGS

SCILLA	Summer Campaign for Intercomparison of Lunar measurements of Lindenberg's Aerosol: Campaign at DWD/MOL-RAO in Lindenberg (Tauche, Germany), August/September 2020
SKYNET	SKY Measurements NETwork: AOD and aerosol properties measurements network using Prede-POM instrument
SSA	Single Scattering Albedo
STSM	Short Term Scientific Mission: Grant possibility of a COST Action (including a visit to another institute)
TOC	Total Ozone Column: Columnar integrated amount of Ozone in DU (Dobson Unit)
UVa	University of Valladolid, Valladolid, Spain
VM	Virtual Mobility: grant possibility of of a COST action.
WG	Working Group
WMO	World Meteorological Organisation
WORCC	World Optical Depth Research Calibration Center: Calibration centre of the GAW-PFR AOD measurements network at PMOD/WRC in Davos

Annex Table T2: Description of the campaigns and/or long-term measurements

	Name (Place)	Latitude (°), Longitude (°), Altitude (m)	Start Date - End Date dd.mm.yyyy	Instruments
1	ANACC (Ny-Ålesund)	78.9, 11.9, 7	03.02.2020-14.02.2020	Cimel* (Lunar), PFR, Prede-POM, star photometer, Raman-Lidar, Clidar
2	ASKOS (Cabo Verde)	16.87, -24.99, 2	02.09.2021-28.09.2021, 10.06.2022-30.06.2021, 06.09.2022-26.09.2022	Cimel, HALO wind lidar, PollyXT lidar, EVE lidar, Microwave Radiometer, UAV-based aerosol instruments (OPCs, backscattersonde, sample collection), ATLID/Aeolus
3	BLOOM, BLOOM II (Guadiana)	37.91, -3.23, 370	18.05.2022-21.06.2022, 28.03.2023-31.05.2023	Cimel, HALO Photonics Doppler lidar, ceilometer, anemometers, trace gas analyzers (LICOR), Pollen samplers, radiometers
4	CHARADMExp (Crete, Greece)	35.34, 25.67, 250	16.06.2014-21.07.2014	Cimel, Microtops, Microwave radiometer, HALO wind lidar, EMORAL lidar, PollyXT lidar
5	Cyprus 2021 Fall (Cyprus)	35.04, 33.06, 500	18.10.2021-18.11.2021	Cimel, Prede-POM, Lidar, Ceilometers, UAV-based aerosol instruments (OPCs, backscattersonde, sample collection)
6	FRC-IV, FRC-V (Davos)	46.82, 9.84, 1588	07.10.2021-19.10.2021, 07.10.2021-19.10.2021	Cimel, PFR, Prede-POM, Middleton, MFRSR, Microtop, PSR, Solar Spectral Irradiance Meters (SSIMs) Cimel, PFR, Prede-POM, Middleton, PSR, QASUME, CW photometer
7	MAPP (Izaña)	28.31, -16.5, 2373	02.09.2022-22.09.2022	Cimel, PFR, Prede-POM (lunar), PSR
8	Montevideo, Uruguay	-34.92, -56.17, 58	14.02.2022-23.02.2022, 02.09.2022-08.11.2022	CIMEL, EKO, pyranometer
9	PRE-TECT (Crete, Greece)	35.34, 25.67, 250	01.04.2017-30.04.2017	CIMEL, Prede-POM, pyranometer, HALO wind lidar, PollyXT lidar, Microwave Radiometer

10	QUATRAM1 (Davos) QUATRAM1 (Rome) QUATRAM2 (Davos) QUATRAM2 (Rome) QUATRAM3 (Rome)	46.82, 9.84, 1588 41.9, 12.52, 83 46.82, 9.84, 1588 41.9, 12.52, 83 41.9, 12.52, 83	19.08.2017-31.08.2017, 22.09.2017-03.11.2017, 24.07.2018-19.10.2018, 01.05.2019-30.09.2019, 03.09.2021-30.09.2021	Prede-POM, PFR PFR, Cimel, Prede-POM, Middleton, Pandora, MFRSR, Microtop PFR, Prede-POM PFR, Cimel, Prede-POM, Pandora Prede-POM, Cimel (Lunar), PFR, Pandora
11	SAVEX-D (Cape Verde)	14.92, -23.51, 70	06.08.2015-25.08.2015	Cimel, Prede-POM, aircraft measurements
12	SCILLA (Lindenberg)	52.21, 14.12, 121	25.08.2020-08.09.2020	Cimel (Sun+Lunar), Prede-POM (Sun+Lunar), PFR (Sun+Lunar), star photometer, lidars (Raman, spectral+polar), ceilometers, PSR, Microwave radiometer, UV spectrometers, pyranometers, pyrheliometers, pyrgeometers, Brewers, Dobson, all-sky camera, Radiosondes, weather station
13	BIOSURE (Vilnius, Lithuania) (Warsaw, Poland)	54.67, 25.28, 112 52.24, 21.02, 100	15.06.2022-ongoing 06.06.2021-ongoing	Cimel
14	IE-BAS (Sofia, Bulgaria)	42.65, 23.39, 631	01.02.2021-28.02.2021, 05.05.2020-ongoing	Cimel, Lidar (for campaign only in 2021)
15	SCARCE (Aguamarga)	36.94, -2.03, 205	18.07.2023-15.10.2023	Cimel, HALO Photonics Doppler lidar, ceilometer, dry deposition sampler, anemometers, trace gas analysers (LICOR), radiometers
16	EVASO (Évora, Portugal)	38.57, -7.91, -	2003-ongoing	Cimel, lidar, ceilometer, MW radiometer, DOAS spectrometer, all-sky camera, nephelometer, APS, MAAP, TEOM, high volume sampler, air quality analysers, UV radiometers, pyranometers, pyrheliometer, MFR7, weather station
17	Lampedusa Climate Observatory (Lampedusa)	35.52, 12.63, 45	1997-ongoing	Cimel (Sun+lunar), lidar, MFRSR, Middleton, ceilometer, Brewer, SW (global, direct, diffuse, reflected) and LW (incoming and outgoing) radiometers, VIS-NIR spectrometers, IR pyrometer, meteorological station, cloud radar, microwave radiometer

18	OPAR (Maïdo, Reunion Island)	-21.08, 55.38, 2160	01.01.2012-ongoing	Cimel, lidars (aerosol, Ozone (Troposphere & Stratosphere), Temperature, Wind), Ceilometer, Microwave radiometer, UVE radiometer, Radiation measurements (BSRN), Disdrometer, Rain gauge, All-sky camera, FTIRspectrometers, Radio-soundings, In-situ instruments (CPC, aethalometer, etc.), Radar
19	RMI and IASB-BIRA (Brussels/Uccle)	50.79, 4.36, 100	07.2006-ongoing	Cimel, Brewer
20	Salto, Uruguay	-31.28, -57.92, 56	02.01.2022-ongoing	EKO spectroradiometer, pyranometer, pyrheliometer, all sky camera
21	FMI (Sodankylä, Finland)	69, 25, 179	06.2015-ongoing	Cimel, Brewer
22	Svalbard		2002-2021, ongoing	Cimel, PFR, Middleton, Microtops, Brewer, lidar
23	AREAD (Shipborne: Vigo, Spain - Abu Dhabi, UAE)	-, -, 0	25.11.2022-20.12.2022	Cimel, Ceilometer, surface-based in-situ

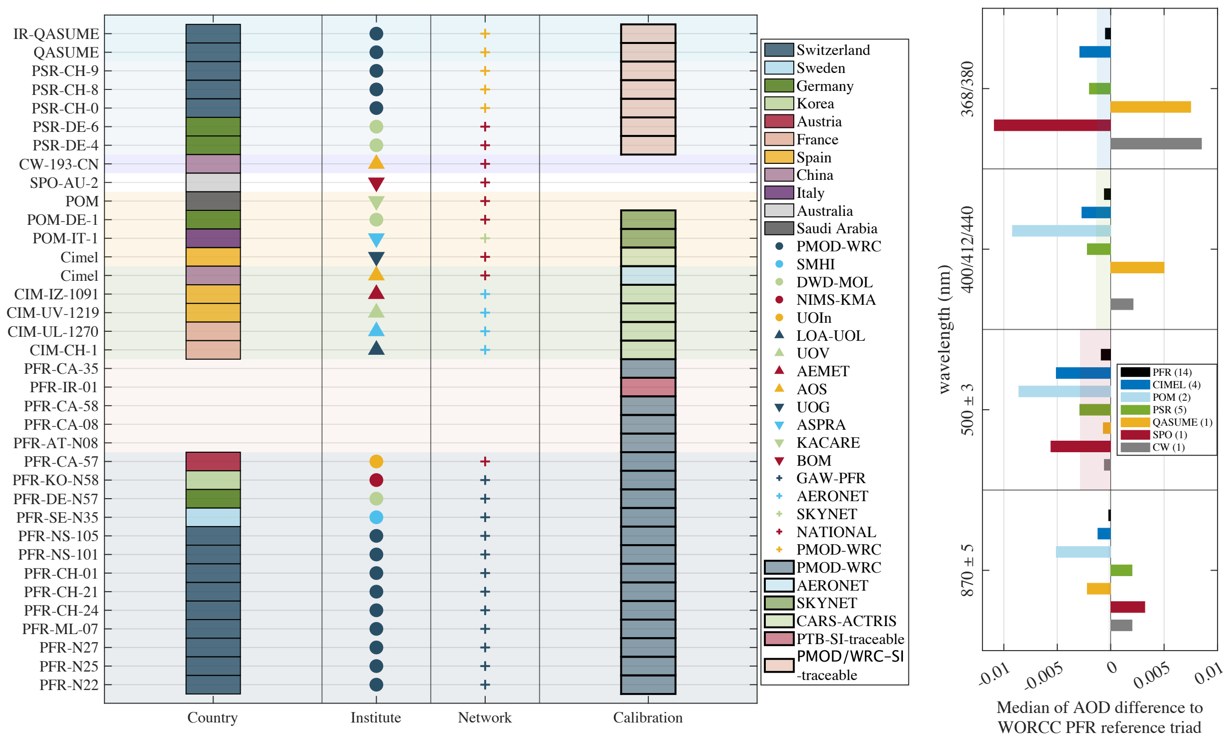
Annex Table T3: Overview of the datasets and access

	Name	Dataset	Data availability	Contact
1	ANACC	AOD, AE, backscatter profiles, extinction, temperature, pressure, humidity	Valladolid, PMOD/WRC, AWI	Carlos Toledano, Natalia Kouremeti, Christoph Ritter
2	ASKOS	AOD, AE, AIP, Backscatter and Extinction coefficient, VLDR, Wind, RH	ESA Data Center	Holger Baars, Eleni Marinou, Peristera Paschou, Franco Marenco, Maria Kezoudi
3	BLOOM, BLOOM II	AOD, AE, AIP, wind profiles, wind shear, turbulence, aerosol particle fluxes, RCS, ABLH, pollen concentration	Only AERONET data	Juan Luis Guerrero Rascado
4	CHARADMExp	AOD, AE, AIP, RH, Wind, Range-corrected signals, Backscatter & Extinction coefficient, VLDR	NOA	Vassilis Amiridis, Eleni Marinou, Alexandra Tsekeri
5	Cyprus 2021 Fall	AOD, AE, AIP, height-resolved particle size-distribution, aerosol backscattering, dust mineralogical composition	On request	Franco Marenco, Maria Kezoudi, Alkistis Papetta
6	FRC-IV, FRC-V	AOD, AE	On request	Stelios Kazadzis, Natalia Kouremeti
7	IZAÑA-MAPP	AOD, AE, CC	CNR, AEMET, AERONET	Monica Campanelli
8	Montevideo, Uruguay	AOD, AE, CC	On request	Paola Russo, Agustín Laguarda
9	PRE-TECT	AOD, AE, AIP, GHI, UV GHI, Wind, RH, Backscatter & Extinction coefficients, VLDR	NOA	Vassilis Amiridis, Eleni Marinou, Alexandra Tsekeri, Monica Campanelli
10	QUATRAM1, QUATRAM1, QUATRAM2, QUATRAM2, QUATRAM3	AOD, AE, CC	CNR Data centers, PMOD/WRC	Monica Campanelli

11	SAVEX-D	AOD, AE, AIP (focused in size distributions)	AERONET, On request	Victor Estelles, Franco Marenco
12	SCILLA	AOD, AE, AIP, TOD, GHI, UV-GHI, Backscatter & Extinction	DWD, PMOD/WRC, Valladolid	Lionel Doppler
13	BIOSURE	AOD, AE, AIP	AERONET	Iwona Stachlewska
14	IE-BAS	AOD, AE, AIP, range-corrected signals, backscatter coefficients, backscatter-related Ångstrøm exponent α	AERONET, Lidar: On request	Tanja Dreischuh, Tsvetina Evgenieva, Zahary Peshev
15	SCARCE	to be completed	Ongoing analysis	Juan Luis Guerrero Rascado
16	EVASO	AOD, AE, AIP	AERONET, EARLINET, E-PROFILE	Maria João Costa; Daniele Bortoli
17	Lampedusa Climate Observatory	AOD, AE, AIP	On request	Daniela Meloni
18	OPAR		NDACC, SHADOZ, TCCON/ICOS, AERONET, GAW-PFR, EBAS	Michael Sicard
19	RMI and IASB-BIRA	AOD, AE, AIP, UVAOD	AERONET, IASB-BIRA, RMI	Alexander Mangold
20	Salto, Uruguay	AOD, AE, CC	On request	Paola Russo
21	Sodankylä, Finland	AERONET products, EUBREWNET AOD 320 nm	AERONET, EUBREWNET	Veijo Aaltonen, Kaisa Lakkala
22	Svalbard	AOD, AE, AIP	AERONET, GAW Network	
23	AREAD	TBD	On request	Alkistis Papetta, Franco Marenco

AOD: aerosol optical depth, AE: Ångström exponents, RH: relative humidity, GHI: global horizontal irradiance, ABHL: atmospheric boundary layer height, AIP: aerosol inversion products, CC: calibration constants, VLDR: volume linear depolarization ratio

Annex Figure F1: Description of datasets (parameters are colour bars) and data availability (colour markers in the right part of the plot) for each campaign (y axis on the left of the plot)



Appendices: Links to associated documents

Appendix A1: List of existing campaigns

GOOGLE SHEET: "COST-HARMONIA Deliverable D1.1: List of existing campaigns // Stand October 2023" Available in viewer modus at this link:

https://docs.google.com/spreadsheets/d/1hauERV8nbK5tUmRDlc7erMM99o-os6Wjl8ronJAPMaE/edit?usp=sharing

Appendix A2: Special selected campaigns: Overview - Intern HARMONIA presentation

PDF document (.pptx conversion): COST-HARMONIA_Overview-Selected-Campaigns.pdf

Title: "Special selected campaigns: Overview - Intern HARMONIA presentation"

Available via this link:

https://harmonia-cost.eu/wp-content/uploads/2023/10/COST-HARMONIA_Overview-Selected-Campaigns.pdf

Appendix A3: Doppler et al. 2023 - Learnings from selected campaigns - EMS 2023 Presentation

PDF document (.pptx conversion): COST-HARMONIA_EMS2023_Learnings-selected-Campaigns.pdf

Title: "Doppler et al. 2023 - Learnings from selected campaigns - EMS 2023 Presentation"

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