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Report on Aerosol Measurement Requirements for Different User Communities

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Report on Aerosol Measurement Requirements for Different User Communities

1. Introduction

This deliverable presents the consolidated requirements of various user communities concerning aerosol optical property measurements, based on discussions and outcomes from the first and second Harmonia workshops (D3.1a and D3.1b), and supported by insights from related *training schools, surveys, and validation campaigns*. The objective is to map these requirements in terms of accuracy, uncertainty, and spatiotemporal resolution, while highlighting sector-specific priorities and challenges. The findings will inform subsequent Harmonia deliverables, especially D3.3 (white paper on aerosol accuracy). The main objective is to document user expectations concerning the accuracy, uncertainty, and spatiotemporal resolution of aerosol measurements derived from ground-based sun photometers. This forms the foundation for future actions under HARMONIA, including the development of a white paper (D3.3) and recommendations for instrumentation, data harmonization, and network coordination. The findings and recommendations presented in this report are in relation with leading international standards and initiatives. These include the GCOS Implementation Plan 2022 (GCOS-244), which defines aerosol optical depth (AOD) as an essential climate variable and emphasizes traceability and long-term consistency in aerosol observations. It also adheres to WMO Global Atmosphere Watch (GAW) guidelines for calibration and network harmonization, and supports the priorities of the Horizon Europe programme, particularly regarding Earth observation integration, open data policies, and user-driven innovation in atmospheric monitoring.

2. Radiometric Measurement Techniques

Aerosol optical properties such as Aerosol Optical Depth (AOD), Single Scattering Albedo (SSA), Ångström exponent, and particle size distribution play a crucial role in multiple sectors. This deliverable focuses on identifying the specific requirements that different communities place on aerosol data. The work builds on WG3's mandate to enhance the usability of aerosol measurements across disciplines. This document outlines the role of aerosol data in different application domains, current capabilities, and infrastructure, identified gaps, and strategic recommendations based on feedback from users. This report contributes to broader frameworks such as WMO-GCOS and aligns with the objectives of ACTRIS, AERONET, and EarthCARE validation efforts. The report also aligns with broader international frameworks that define global standards and priorities for atmospheric observations. Notably, the GCOS Implementation *Plan 2022 (GCOS-244)* outlines essential climate variables (ECVs), including aerosol optical depth (AOD), and emphasizes the importance of long-term, high-quality observations to support climate adaptation and mitigation strategies. This plan provides concrete recommendations for enhancing the global climate observing system and is available through the GCOS portal. In parallel, the World Meteorological Organization (WMO) provides detailed guidelines on atmospheric composition measurements, calibration, and quality assurance through its *Global Atmosphere Watch (GAW) programme*. These standards ensure that aerosol observations from networks such as AERONET and GAW-PFR are traceable, interoperable, and

suitable for satellite validation and climate services. Relevant documentation can be accessed via the WMO GAW portal. Furthermore, the report supports the Horizon Europe research and innovation programme's objectives in Earth observation, data integration, and climate resilience. *Horizon Europe funds* a wide range of projects aimed at enhancing environmental monitoring and ensuring that ground-based, satellite, and model-based systems are interconnected to serve both policy and operational users. Information on relevant calls and thematic clusters can be found on the Horizon Europe website.

3. Methodology

The development of this report is grounded in a comprehensive review of presentations and discussions from two summer schools (Berlin 2024 and Izana 2025) the two primary WG3 workshops—held in Athens (2023) and Limassol (2025)—alongside an in-depth analysis of feedback collected through WG3 meetings, online surveys, etc. These interactions provided valuable insights into the priorities and challenges faced by user communities working with aerosol ground-based photometers. Ground-based sun photometers retrieve aerosol properties using direct sun and sky radiance observations, including almucantar and principal plane scans. These systems provide stable long-term records that are critical for climate research, air quality monitoring, and satellite validation. However, they face operational limitations such as incomplete diurnal coverage and challenges in dense urban deployment. The most prominent global networks supporting sun photometric observations include AERONET, SKYNET, and GAW-PFR. AERONET offers standardized, quality-assured data with global coverage and is widely used for satellite validation and aerosol climatology. SKYNET specializes in sky radiance measurements and has a strong presence in Asia, while GAW-PFR, operated under the World Meteorological Organization's Global Atmosphere Watch, provides high-accuracy reference data and supports instrument intercalibration efforts. Sun photometers retrieve a range of key atmospheric parameters including aerosol optical depth (AOD), single scattering albedo (SSA), Ångström exponent (AE), and precipitable water vapor. These parameters are essential for quantifying aerosol load, particle size and absorption characteristics, and water vapor content—all of which are critical for applications in climate modeling, radiative transfer simulations, and solar energy forecasting. To extract these parameters, photometers rely on radiometric techniques such as spectral extinction measurements at multiple wavelengths. The data are processed using sophisticated inversion algorithms—such as those developed for AERONET—which retrieve aerosol microphysical and optical properties, including size distributions and complex refractive indices. These techniques are essential for identifying aerosol types (e.g., dust, smoke, pollution) and evaluating their radiative impacts. Robust calibration and quality assurance protocols are indispensable for ensuring the reliability of sun photometer measurements. The Langley plot method, typically performed at high-altitude sites with stable atmospheric conditions, allows for the absolute calibration of direct sun channels. Additionally, the triplet quality check, which analyzes the consistency of three consecutive measurements, helps detect transient variability due to clouds or instrumental drift, thereby maintaining high data integrity.

Summer schools (Sky over Berlin - Berlin 2024 and Above the clouds - Izana 2025)

<https://harmonia-cost.eu/skyoverberlin/>; <https://harmonia-cost.eu/abovetheclouds/>

In addition to technical infrastructure and measurement protocols, HARMONIA has prioritized capacity building and interdisciplinary training through its thematic summer schools. Two major events—Sky Over Berlin and Above the Clouds—offered hands-on experience with sun photometers

and other aerosol remote sensing instruments. These schools brought together early-career researchers, instrument operators, and domain experts to explore the scientific principles and practical challenges of aerosol optical property retrievals. Participants engaged in real-time data collection, calibration exercises, and inversion analysis using platforms such as AERONET and ACTRIS. The schools also fostered collaboration across disciplines and contributed to harmonizing observational practices across Europe. In this context, the summer schools played a critical role in linking ground-based aerosol networks with emerging user needs and long-term research strategies supported by HARMONIA.

WG3 1st workshops—held in Athens (2023)

https://harmonia-cost.eu/wp-content/uploads/2023/10/Harmonia_D3_1a.pdf

The first WG3 workshop, held in Athens in September 2023, served as a foundational event for engaging aerosol data users and identifying cross-sectoral needs. Hosted at the Academy of Athens, the workshop gathered experts from academia, operational agencies, and industry to discuss the role of aerosol optical property measurements in climate, health, aviation, and renewable energy applications. Eleven invited speakers presented topics ranging from satellite validation and radiative transfer to dust modeling and solar energy forecasting. The workshop emphasized the importance of harmonized, high-quality ground-based observations and highlighted user expectations for vertical resolution, spectral coverage, and data accessibility. The detailed outcomes are documented in Deliverable D3.1a, which forms a key reference for the development of this D3.2 report.

WG3 2nd workshops—held in Limassol (2025)

The second WG3 workshop, documented in Deliverable D3.1b, was held in Limassol, Cyprus, in June 2025 and built upon the foundations laid during the Athens meeting. The event brought together researchers, stakeholders, and early-career scientists to explore the practical implementation and validation of aerosol measurements in operational and scientific frameworks. Sessions focused on the integration of ground-based sun photometric observations with satellite products (such as those from EarthCARE), the role of aerosol data in solar radiation forecasting, and user requirements from diverse sectors including energy, climate modeling, and aviation. Special attention was given to real-world applications and user feedback gathered through interactive discussions and live demonstrations at the CARO ACTRIS station. The deliverable captures the evolution of user engagement strategies and directly informed the sectoral analysis presented in this D3.2 report. In-depth analysis of feedback collected through WG3 meetings

Online survey

This short survey was conducted as part of the activities of Working Group 3 (WG3) of the COST Action HARMONIA, which aims to identify and address the needs of user communities relying on aerosol optical property measurements. The focus of the survey was to gather targeted feedback on the accuracy, uncertainty, and spatiotemporal resolution required from ground-based sun photometer aerosol data, in order to support various applications including climate research, air quality monitoring, satellite validation, and solar energy forecasting.

This short survey is part of the work of the COST action HARMONIA Working Group 3, focusing on user requirements on the accuracy, uncertainty and spatiotemporal resolution of aerosol measurements needed for their activities.

- For what purpose do you use the ground-based photometer aerosol data?
- What are your accuracy requirements (for ground-based photometer aerosol data)

- Just write OK if the current data accuracy is fine for you
- What are your uncertainty requirements (for ground-based photometer aerosol data)
- Just write OK if the current data uncertainty is fine for you
- What are your spatiotemporal resolution requirements (for ground-based photometer aerosol data)
- Just write OK if the current data spatiotemporal resolution is fine for you
- Any additional comment or request?

4. Literature Review

Radiometric aerosol measurements have been the subject of extensive research, especially in connection with climate modeling, satellite validation, solar energy optimization, and air quality monitoring.

AERONET and Network-Based Retrievals: *Holben et al. (1998)* established the Aerosol Robotic Network (AERONET) as a global, standardized network of CIMEL sun photometers, designed to deliver high-quality aerosol optical depth (AOD) and sky radiance data for inversion-based retrievals. Over time, enhancements in processing algorithms—especially with the introduction of Version 2 and 3 (*Dubovik et al., 2002; 2021*)—have expanded AERONET’s capabilities to include single scattering albedo (SSA), aerosol size distribution, and complex refractive index. These properties are essential for communities focused on climate modeling, satellite validation, and air quality monitoring, as they directly feed into radiative transfer simulations and atmospheric correction schemes. AERONET’s global reach and long-term continuity make it a cornerstone for users needing traceable, validated aerosol data.

Spectral and Directional Techniques: The use of almucantar and principal plane scan geometries, as analyzed in *Dubovik and King (2000)*, enhances the ability to retrieve aerosol microphysical properties with greater sensitivity to particle shape and absorption characteristics. This is especially important for air quality researchers and solar energy planners, who require accurate estimates of coarse-mode versus fine-mode aerosols, and absorption properties relevant to UV and visible radiation. These methods are directly connected to user demands for improved SSA retrievals under variable aerosol conditions, such as during biomass burning or dust transport events.

Calibration and Uncertainty Management: Reliable calibration is essential to meet the accuracy requirements highlighted by modeling and assimilation communities. The Langley plot technique, used primarily at high-altitude sites, ensures absolute calibration of the direct sun channels. Comparative studies by *Kazadzis et al. (2018)* emphasize the need for inter-network calibration consistency, particularly between AERONET and GAW-PFR, to support interoperability and traceability. Meanwhile, uncertainty quantification work directly supports user needs for transparent and well-documented uncertainty budgets, especially when integrating ground-based measurements into operational systems such as CAMS. These findings validate user calls for more rigorous uncertainty reporting, as identified during WG3 consultations.

Application-Specific Studies: Table: Application-Specific Research and Related User Requirements

Application Domain	Key Studies	Main Findings	Related User Requirements
Solar Energy	Kazadzis et al. (2021)	AOD and SSA uncertainties can lead to 20–30% errors in energy yield estimates (notably in high aerosol variability regions).	High-resolution, site-specific aerosol inputs; increased spatial density of sun photometer stations, especially in urban and arid areas.
Satellite Validation	Kinne et al. (2013), CCVS (2023)	Ground-based data are essential for validating aerosol satellite products; emphasize co-location, cloud–aerosol separation, and data traceability.	High temporal frequency, metadata quality, vertical representativeness; adherence to strict co-location standards for matchup datasets.
Dust and Climate	Solomos et al. (2022)	Dust modeling requires vertical aerosol profiles and coarse-mode AOD to improve radiative impact estimation.	Vertical resolution, IR spectral range extension, refined SSA for dust aerosols; relevant for modelers and regional forecasters.
Health and UV Exposure	Fountoulakis et al. (2018, 2023)	SSA and AE influence UV forecasts and public health outcomes; spatial coverage in cities is insufficient.	SSA and AE retrievals in the UV range; improved data availability in urban areas for UV index modeling and public health monitoring.

5. User Requirements Across Disciplines

Solar Energy Sector: The solar energy sector demands aerosol optical depth (AOD), direct normal irradiance (DNI), and global horizontal irradiance (GHI) data with high temporal resolution (1–15 min) at urban to micro-urban scales (100 m – 1 km). These data are essential for short-term solar forecasting, optimizing photovoltaic (PV) performance, and adjusting for soiling losses due to dust and particulate deposition. High-frequency measurements enable integration into real-time operational forecasting systems. Particular emphasis is placed on aerosol impacts under clear-sky and partially cloudy conditions, where irradiance fluctuations are most sensitive to atmospheric composition. The solar energy sector demands high-frequency aerosol measurements, particularly AOD, DNI, and GHI, to support short-term forecasting and optimize the performance of photovoltaic (PV) and concentrated solar power (CSP) systems. Users require temporal resolutions as fine as 1–15 minutes, especially under clear-sky or partly cloudy conditions, where aerosol variability has a significant influence on surface irradiance. Measurements must be available at urban to micro-urban scales (100 m – 1 km), to account for local pollution, dust resuspension, and urban heat island effects that influence aerosol distribution and radiative transfer. Additionally, the impact of aerosol soiling on PV panels (e.g., from mineral dust and anthropogenic pollution) necessitates accurate aerosol load estimation to evaluate energy yield losses and inform cleaning schedules. In D3.1b, Kazadzis,

Kazantzidis, and Brito emphasized these requirements during their presentations and discussions, particularly highlighting the role of AOD and SSA in solar resource forecasting and PV plant performance modeling in diverse environments—from Southern Europe to desert-prone regions. Their contributions demonstrated how sun photometer data feed into nowcasting systems and soiling loss models, especially where satellite data lack sufficient temporal or spatial granularity. Meanwhile, in D3.1a, Blanc et al. (2014) presented a detailed review on how aerosol variability influences surface irradiance and solar energy generation, especially Direct Normal Irradiance (DNI), which is highly sensitive to aerosol load and composition. Their findings also support the integration of aerosol-aware correction models into systems such as CAMS, HelioClim, and other operational solar radiation databases. Together, these studies underscore the sector's demand for site-specific, near-real-time aerosol data, with clearly defined uncertainties and harmonized measurement protocols, in order to support energy planning, grid management, and solar technology deployment in climate-sensitive regions.

References: Kazadzis, Kazantzidis, Brito (D3.1b); Blanc (D3.1a)

Atmospheric Modeling and Reanalysis: This sector requires assimilation-ready aerosol datasets, especially AOD and vertically resolved aerosol extinction profiles, with well-characterized uncertainties and traceable metadata. Data must be available within 1–3 hours of acquisition to support operational weather and chemical data assimilation systems. Harmonization across sources (e.g., AERONET, ACTRIS, satellite) is vital to ensure intercomparability and reduce bias in aerosol-radiation-cloud interactions in numerical models. Vertical resolution (≤ 500 m) and full column coverage (surface to tropopause) are considered critical. During the WG3 workshop in Limassol (D3.1b), Solomos presented validation and assimilation studies using the METAL-WRF model, which demonstrated how the inclusion of vertically resolved extinction profiles from lidar and sun photometers significantly improved the model's representation of dust transport and radiative forcing over the Eastern Mediterranean. He emphasized the importance of profile data for cloud-aerosol coupling and short-term forecasting under high aerosol loading. In D3.1a, Ades highlighted the role of data fusion between satellite and ground-based observations in CAMS aerosol reanalysis. He stressed the need for well-characterized uncertainty estimates, temporal continuity, and metadata traceability for successful assimilation. His contribution also pointed to current limitations in vertical representativeness and called for improved calibration alignment across contributing datasets. These presentations reinforced the requirement for high-frequency, harmonized, and profile-resolved aerosol observations to support assimilation workflows in atmospheric and climate modeling systems.

References: Solomos (D3.1b), Ades (D3.1a)

Satellite Validation: Satellite product validation efforts necessitate ground-based reference data that are spatially and temporally collocated with satellite overpasses, preferably within ± 30 minutes and 10 km of the satellite pixel center. Required parameters include AOD, Single Scattering Albedo (SSA), Ångström Exponent (AE), and vertical extinction profiles across multiple wavelengths (UV–NIR). Data must include full metadata (e.g., instrument calibration history, retrieval algorithm version, environmental conditions) and meet traceability standards defined by CEOS and WMO. Multi-angle and sun-photometric measurements are especially valuable for satellite algorithm development and uncertainty assessment. During the Limassol workshop (D3.1b), Meloni presented case studies comparing ground-based retrievals to spaceborne aerosol products, emphasizing the sensitivity of

satellite-derived SSA and AE to the availability and quality of collocated AERONET data. He illustrated how temporal mismatch and calibration drift could introduce biases, particularly under complex aerosol conditions such as urban haze or desert dust events. Marinou discussed the use of lidar profiles and sun photometry to validate EarthCARE aerosol and cloud retrievals, stressing the need for high vertical resolution and synchronized surface observations. Her contribution highlighted the benefit of synergistic measurements (e.g., photometer + lidar) in resolving the vertical aerosol structure necessary for radiative transfer closure studies. Vandenbussche (D3.1b) elaborated on the requirements for metadata traceability and consistent calibration across networks. She emphasized the challenges associated with harmonizing retrieval algorithms and pointed to the usefulness of reference instruments and mobile platforms for campaign-based validation. In the earlier Athens workshop (D3.1a), Koukouli reviewed the CEOS-validated matchup protocols for Sentinel products, noting the importance of automated co-location tools, temporal interpolation methods, and multi-network harmonization. Her work provided practical insights into the operational use of AERONET and ACTRIS data for ongoing validation campaigns. Together, these contributions underscore the validation community's need for high-fidelity, traceable, and spatiotemporally synchronized aerosol measurements, particularly for the advancement of next-generation satellite aerosol retrievals.

References: Meloni, Marinou, Vandenbussche (D3.1b); Koukouli (D3.1a)

Public Health and Urban Air Quality: Public health applications require surface-level aerosol concentration proxies, especially PM_{2.5} and PM₁₀, derived from column-integrated AOD. There is a need for near-real-time data (<1 hour latency) with urban spatial resolution (≤ 1 km), enabling correlation with health indicators such as respiratory morbidity, skin cancer incidence, and vitamin D synthesis rates. Additionally, UV index monitoring is critical for public advisories. The integration of remote sensing with in situ monitoring stations is necessary to downscale columnar data to human exposure levels.

References: Fountoulakis, Charalampous (D3.1b); Vasardani (D3.1a)

Agriculture: In agriculture, aerosol observations support the monitoring of dust and smoke intrusions, which influence crop health, photosynthetically active radiation (PAR), and UV-induced plant stress. Users require daily to seasonal forecasts, especially during critical growth periods, with real-time alerts for extreme aerosol events (e.g., dust storms). Integration with solar radiation and UV measurements is crucial for precision agriculture. Spatial scales range from field level (~ 1 km) to regional (~ 10 km). In D3.1b, Fountoulakis presented results from Eastern Mediterranean stations showing how variations in SSA and AE influence biologically effective UV radiation, a parameter directly linked to health impact assessments. He emphasized the necessity of integrating AOD measurements with UV radiative transfer models to improve population exposure estimates under changing atmospheric conditions. Charalampous (D3.1b) provided additional insights into the operational challenges of urban-scale aerosol mapping, emphasizing the limitations of columnar data in areas with complex topography and microclimates. He advocated for hybrid approaches that combine sun photometry, lidar, and in situ monitoring. In D3.1a, Vasardani addressed the issue of temporal resolution for air quality alerts, noting that the current latency of validated sun photometer data limits their usefulness in issuing rapid public health warnings. She called for the development of quick-look data products with uncertainty flags, suitable for real-time integration into health surveillance systems and mobile advisory tools.

References: Charalampous, Marengo (D3.1b); Zerefos (D3.1a)

Climate Science: Climate applications necessitate long-term, stable time series of aerosol optical properties, especially AOD, fine/coarse mode decomposition, and spectral SSA, with well-characterized and consistent uncertainties. Monthly to annual temporal resolution suffices, but spatial homogeneity and multi-decadal continuity are critical for assessing aerosol radiative forcing and trends in climate models. Emphasis is placed on global networks with calibrated, inter-comparable instruments, such as AERONET and ACTRIS. Amiridis (D3.1a) addressed the integration of lidar and photometer data to constrain vertical distributions in reanalysis systems and satellite products. His work on EARLINET-ACTRIS synergies highlighted how long-term backscatter and extinction profiles, combined with surface AOD and SSA, improve understanding of vertical aerosol loading, a key factor in estimating aerosol-induced atmospheric heating. In D3.1b, Solomos applied aerosol climatologies and regional model simulations using METAL-WRF to investigate dust transport and climate interactions in the Mediterranean. He emphasized the importance of long-term validation datasets for understanding seasonal shifts in dust source strength and radiative impact. Meloni (D3.1b) further supported this by presenting multi-year ground-based records used in satellite validation and climate process studies, calling for consistent retrieval algorithms, network coordination, and the development of global radiative closure datasets that bridge ground and space observations. Together, these contributions reinforce the climate sector's demand for long-term, globally harmonized, and uncertainty-qualified aerosol datasets to reduce model biases, constrain radiative forcing estimates, and track anthropogenic and natural aerosol trends over time.

References: Kinne, Amiridis (D3.1a); Solomos, Meloni (D3.1b)

Aviation: Aviation safety requires detailed vertical aerosol profiles, focusing on dust, smoke, and volcanic ash, with hourly updates and spatial resolution at the airport level (1–10 km). Latency must be less than 1 hour to support flight planning and airborne hazard avoidance. Integration with forecast models is necessary for alert generation and risk assessment. Priority is given to aerosol backscatter and extinction profiles from lidar, supplemented by aerosol type classification where possible. The most critical parameters include aerosol backscatter and extinction coefficients derived from ground-based lidar systems, as well as aerosol typing and altitude classification to support risk assessments and integration with numerical weather prediction (NWP) and early warning systems. These data are increasingly incorporated into aviation decision support systems, especially in regions prone to dust intrusions (e.g., Sahara outflow), biomass burning, or volcanic eruptions. In D3.1a, Vasardani presented operational requirements from civil aviation authorities and highlighted case studies where insufficient vertical resolution or delayed data impacted risk management for dust-influenced airspace in Greece and Cyprus. She underscored the value of ACTRIS lidar stations as core observational assets and recommended improved data sharing protocols and alert generation tools. Solomos (D3.1b) contributed detailed simulations using the METAL-WRF system, demonstrating how assimilation of real-time lidar-derived aerosol extinction profiles can improve the prediction of dust layer altitude, a key factor in determining engine exposure risk and visibility impairment. He emphasized the importance of collocating lidar systems with airports and harmonizing them with satellite-based early warning platforms (e.g., MSG, CALIPSO). Marengo (Dust-DN) addressed the specific case of volcanic ash and Saharan dust, two of the most critical aerosols in aviation hazard monitoring. He presented work from the SDS-WAS network and EUMETSAT collaborations, noting how aerosol optical depth alone is insufficient for aviation applications without vertical context. His recommendations included improved synergy between lidar, ceilometers, and forecast models, and the need for continuous vertical profiling at major transit hubs and vulnerable regional airports. These contributions collectively highlight the aviation community's demand for real-time, vertically

resolved, and hazard-specific aerosol data, emphasizing the role of lidar and integrated observation systems in ensuring safe airspace management and early warning capabilities.

References: Vasardani (D3.1a), Solomos (D3.1b), Marengo (Dust-DN)

Urban Planning, Insurance, and Emerging Use Cases: Urban stakeholders require high-resolution irradiance and aerosol attenuation data to support solar cadastre mapping, building-integrated PV potential estimation, and climate resilience planning. Measurements should be spatially resolved to building block level (~50 m) and temporally resolved on an hourly basis. This sector benefits from integrated tools combining remote sensing, GIS, and aerosol modeling to quantify solar resource variability and risk exposure. Accurate urban morphology and 3D radiative transfer models are increasingly important. In D3.1b, Brito presented solar cadastre work in Lisbon and demonstrated how sun photometer-based AOD measurements, when integrated with urban geometry datasets, improve estimates of realistic solar energy potential at the façade and rooftop levels. He emphasized the role of cloud–aerosol separation in optimizing irradiance prediction in cities prone to haze and frequent boundary layer aerosol buildup. Amaro (D3.1b) explored the role of aerosol-aware irradiance modeling in the context of urban climate risk assessments, noting how fine-resolution aerosol data can improve the reliability of projections related to solar energy generation, air quality exposure, and urban heat island mitigation efforts. Additionally, inputs from the e-shape project provided examples of operational urban services that integrate Copernicus Earth Observation data with local-scale atmospheric inputs. These services include risk assessment dashboards, urban climate analytics, and renewable energy mapping tools designed for municipal use. Together, these efforts underline the growing demand for location-specific, real-time aerosol data in the urban domain. Such data are essential for future-proofing urban energy systems, enhancing climate adaptation plans, and supporting emerging insurance models that factor in environmental variability and exposure.

References: Brito, Amaro (D3.1b); e-shape project inputs

6. Current Capabilities

Observational Infrastructure and Coverage: The current observational infrastructure for aerosol optical property monitoring is built upon several mature international networks, including AERONET, ACTRIS, GAW-PFR, and SKYNET. These networks provide globally distributed, quality-assured sun photometer data, with AERONET alone operating over 600 active sites worldwide. In Europe, ACTRIS enhances observational capacity by integrating photometric, lidar, and in situ measurements. However, coverage gaps persist, especially in urban micro-climates, coastal zones, and high-dust regions such as North Africa and the Middle East. Moreover, the density of stations in developing countries remains insufficient for regional modeling and validation tasks.

Data Availability and Portals: Most networks provide open access to aerosol data through standardized web portals. For example, AERONET offers near-real-time and Level 2.0 quality-assured products, while ACTRIS data are accessible through the ACTRIS Data Centre. The WMO GAW World Data Centre for Aerosols serves as a repository for reference instruments. These portals support bulk downloads, API access, metadata search, and filtering by instrument type, time, and geolocation. However, some users highlighted latency issues, limited vertical profile availability, and inconsistent file formats as technical barriers.

Technological Advancements: Recent advances have improved both instrument design and retrieval algorithms. Innovations include compact, low-maintenance sun photometers (e.g., POM-02, PFR-Lite), integration with mobile platforms (e.g., ships, drones), and the extension of spectral coverage into the UV and IR domains. Algorithmic updates in AERONET Version 3 now support improved inversion stability, better cloud screening, and refined SSA estimation under high aerosol loading. Moreover, automated calibration systems and AI-assisted quality checks are being introduced to increase measurement reliability and reduce human intervention. These technological developments help address growing user demands for real-time access, portability, and extended parameter sets in support of operational and research applications.

7. Gaps and Challenges

Spatial and Temporal Limitations: Despite global progress in sun photometric aerosol monitoring, significant spatial coverage gaps remain—particularly in developing countries, over oceans, and in urban micro-climates. Urban and peri-urban areas often lack sufficient station density to support high-resolution air quality mapping or urban solar energy modeling. Temporal limitations include the inability of sun photometers to operate during nighttime or heavy cloud cover, resulting in data gaps during critical episodes such as dust storms, wildfires, or low-sun seasons in high-latitude regions. Presentations by Brito, Kazantzidis, and Solomos (D3.1b) illustrated how this limitation constrains PV yield prediction, dust event monitoring, and regional climate analysis. Temporal gaps, particularly due to daylight-only operation and cloud interference, were raised as obstacles for both real-time applications and long-term datasets.

Spectral Range Gaps (UV/IR): Most current networks are optimized for visible and near-infrared wavelengths. However, retrieval capabilities in the ultraviolet (UV) and infrared (IR) remain limited, despite strong user interest. The UV range is essential for public health, UV Index modeling, and photochemical analysis, while the IR is critical for detecting coarse-mode aerosols like dust and for satellite-based radiative closure studies. Few instruments are equipped with stable and accurate calibration in these bands, and algorithm development is still ongoing. Presentations by Fountoulakis (UV/health sector, D3.1b) and Meloni and Marinou (IR/satellite validation, D3.1b) stressed that the current spectral limitations restrict multi-sectoral use. Participants agreed that UV-capable and IR-enhanced photometers should be prioritized in network upgrades.

Calibration and Harmonization: While networks like AERONET and GAW-PFR implement rigorous calibration protocols, challenges remain in achieving inter-network harmonization. Disparities in instrument calibration procedures, reference standards, and retrieval algorithms complicate data merging efforts. Users—particularly in modeling and assimilation—require traceable, uncertainty-qualified datasets. The lack of centralized cross-network calibration campaigns and limited use of SI-traceable standards are key obstacles to interoperability and long-term consistency. Presentations by Kazadzis (D3.1a) and Vandenbussche (D3.1b) addressed discrepancies in SSA and AOD retrievals between AERONET and other networks. The need for harmonized protocols, SI-traceable calibration, and joint calibration campaigns was strongly supported, with ACTRIS and GAW seen as platforms to facilitate this alignment.

Real -Time Accessibility and Uncertainty Reporting: Many user communities—including those in forecasting, health, and aviation—have expressed the need for near-real-time aerosol products with clear and quantitative uncertainty estimates. However, current latency ranges from a few hours (in

some AERONET quick-look products) to several days or weeks (for validated Level 2.0 data). Furthermore, uncertainty documentation is inconsistent, with few products offering transparent, algorithm-derived error bars. This reduces the usability of data for operational systems and limits its credibility in risk-based decision-making. In discussions led by Ades, Marinou, and Charalampous (D3.1a and D3.1b), it became clear that the latency of validated data (up to days or weeks) is too high for forecasting, assimilation, and health risk communication. Participants called for quick-look products with uncertainty flags, and emphasized that uncertainty transparency is crucial for credibility in modeling, especially for satellite–ground comparisons and air quality nowcasting.

8. Strategic Recommendations

Building on the identified gaps, stakeholder feedback, and technical discussions during the Athens and Limassol workshops, as well as the Sky Over Berlin and Above the Clouds (Izaña) summer schools, the following strategic recommendations are proposed to improve the utility, accessibility, and harmonization of aerosol measurements across European and global communities.

Network Expansion: Participants across all events strongly advocated for expanding the spatial density of sun photometer installations, particularly in urban, coastal, desert, and mountainous regions. Urban users (e.g. planners, energy analysts, and health agencies) require fine-resolution coverage at the sub-kilometer scale, while satellite and climate users stressed the need for more remote, pristine, or high-altitude sites for background climatologies and calibration. WG3 presentations by Brito, Charalampous, and Kazantzis, as well as training activities in Berlin, highlighted the operational benefits of deploying compact, autonomous photometers in under-monitored zones.

Data Integration and Interoperability: Interoperability across networks such as AERONET, ACTRIS, SKYNET, and GAW-PFR remains a central need, particularly for data assimilation, satellite validation, and modeling. Recommendations include harmonizing retrieval algorithms, metadata standards, and uncertainty quantification. Insights from Vandenbussche (D3.1b), calibration exercises at Izaña, and discussion sessions in Athens emphasized that technical alignment—supported by FAIR data principles—will enhance multi-source integration and reduce systematic biases.

Training, Capacity Building, and Summer Schools: Both summer schools and WG3 events proved critical for knowledge transfer and skill development across research generations and domains. Hands-on calibration, inversion retrievals, and real-time quality control exercises at the Sky Over Berlin and Above the Clouds schools received positive feedback from early-career researchers. It is recommended that summer schools be institutionalized within HARMONIA and partner networks, with expanded participation, multi-language support, and sector-specific modules for energy, health, and satellite communities.

Alignment with Global Initiatives: All recommendations are designed to align with international frameworks, including the GCOS Implementation Plan (GCOS-244), WMO GAW guidelines, and Horizon Europe Earth observation priorities (e.g. CCVS, e-shape). Strategic alignment ensures that European efforts in aerosol monitoring remain interoperable, policy-relevant, and globally visible. Presenters during WG3 and external contributors stressed the value of adhering to CEOS, QA4EO, and Copernicus validation standards for maximizing impact and sustainability.

9. Summary of Requirements

A table summarizing key aerosol measurements requirements across user sectors:

User Sector	Key Measurement Needs	Spatial Resolution	Temporal Resolution	Latency Requirement	Priority Parameters	References
Solar Energy	AOD, SSA, AE, DNI, GHI	100 m – 1 km	1–15 min	< 1 hour	AOD uncertainty < 0.01; SSA uncertainty < 0.03	Kazadzis et al., 2021; Adekanbi et al., 2024; Kazantzidis et al. (D3.1b); García et al., 2025
Atmospheric Modeling / Reanalysis	AOD, extinction profile, SSA, AE	≤10 km	Hourly to 3-hourly	< 3 hours	AOD accuracy < 0.01; vertical resolution ≤ 500 m	Solomos et al., 2022; Ades (D3.1a); Kinne et al., 2013; Dubovik et al., 2021
Satellite Validation	AOD, SSA, AE, vertical extinction	≤10 km (co-located)	±30 min overpass	Near-synchronous	Traceable, metadata-rich; AE ±0.1; SSA ±0.03	Meloni (D3.1b); Marinou (D3.1b); Koukouli (D3.1a); CCVS, 2023; Dubovik & King, 2000
Climate Science	AOD, SSA, AE, spectral inversion	Regional to global	Monthly–seasonal	Not critical	Long-term continuity, calibration traceability	Holben et al., 1998; Dubovik et al., 2021; Kinne et al., 2013; Amiridis (D3.1a); Solomos (D3.1b)

Public Health / UV Monitoring	AOD, AE, PM proxy, UV Index	≤1 km	Sub-hourly	< 1 hour	AE in UV range; AOD uncertainty < 0.02	Fountoulakis et al., 2018; Fountoulakis et al., 2023; Vasardani (D3.1a); Charalampous (D3.1b); Sinyuk et al., 2020
Aviation Safety	Backscatter, extinction profiles, aerosol type	1–10 km (airport)	Hourly	< 1 hour	Vertical resolution < 300 m; latency < 30 min	Marenco (Dust-DN); Solomos (D3.1b); Vasardani (D3.1a); Bazo et al., 2023
Agriculture	AOD, UV, PAR, coarse/fine mode	1–10 km	Daily to weekly	< 1 day	AOD uncertainty < 0.02; UV < 10%	Charalampous (D3.1b); Fountoulakis (D3.1b); Zerefos (D3.1a); García et al., 2025; Alados-Arboledas et al., 2023
Urban Planning / Insurance	AOD, DNI, GHI, sky obstruction	50–100 m	Hourly	< 1 hour	DNI bias < 5%; AOD < 0.01	Brito (D3.1b); Amaro (D3.1b); e-shape; Xia et al., 2021; Adekanbi et al., 2024
Emerging Use Cases (Mobile & Personal)	AOD, PM proxy, SSA (visible)	<100 m	Real-time	< 30 min	Rapid access with uncertainty flags	García et al., 2025; Campanelli et al., 2024; Bazo et al., 2023; Xia et al., 2021

The table above provides a consolidated and literature-supported overview of the key aerosol measurement requirements across major user sectors, as identified through HARMONIA WG3 activities—including dedicated workshops (Athens 2023, Limassol 2025), training schools, targeted



surveys, and stakeholder consultations. These findings are further substantiated by an extensive review of scientific literature covering aerosol radiometry, satellite validation, air quality, and operational forecasting systems. Each sector exhibits clearly differentiated priorities in terms of spatial and temporal resolution, data latency, uncertainty tolerance, and required aerosol parameters. For instance, solar energy and aviation sectors prioritize near-real-time access to aerosol optical depth (AOD), single scattering albedo (SSA), and vertically resolved extinction data, typically with sub-hourly update frequencies and spatial resolution down to 100 meters, especially in urban or airport settings. These requirements reflect the operational demand for accurate and dynamic inputs to nowcasting systems, hazard avoidance protocols, and PV yield optimization models. This sectoral diversity underlines the necessity of customized observational strategies, flexible data services, and investment in next-generation instrumentation (e.g., UV/IR-capable photometers, autonomous calibration systems, miniaturized mobile platforms). It also reinforces the strategic importance of aligning measurement protocols with international frameworks such as ACTRIS, GCOS Implementation Plan (GCOS-244), the WMO GAW program, and Copernicus services. These frameworks collectively emphasize data interoperability, open access, and quality assurance—principles that are essential for advancing the operational and scientific utility of aerosol observations.



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