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

HARMONIA CA21119

Deliverable 4.2

Report on hardware and software evolution needs according to WG3 results.

Authors	Pablo González-Sicilia, Africa Barreto, Roberto Román, Natalia Kouremeti, Stelios Kazadzis, Sara Herrero-Anta, Miguel Huerta, Ilias Fountoulakis, Stavros Solomos
Date	01 September 2026

COST EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY
Funded by the European Union

Table of Contents

Executive Summary

This deliverable (D4.2 – Report on hardware and software evolution needs according to WG3 results) presents the Working Group 4 (WG4) results of the HARMONIA COST Action CA21119 on industry engagement towards innovative hardware and software products for aerosol columnar optical properties measurements. It builds directly on the findings of the companion deliverable **D3.2 - Report on Aerosol Measurement Requirements for Different User Communities** (Toanca et al., 2025), which systematically compiled the requirements of key stakeholder communities through the WG3 workshops held in Athens (D3.1a; 2023) and Limassol (D3.1b; 2025), the HARMONIA summer schools held in Rome (Sorbetto, 2023), Berlin (Sky Over Berlin, 2024), Izaña (Above the Clouds, 2025), and an online survey. This report translates those user requirements into concrete hardware and software evolution needs, based on the scientific results of HARMONIA peer-reviewed publications and the two dedicated WG4 meetings held in Davos (Switzerland) and Valladolid (Spain).

The core finding is that aerosol columnar observing systems must now serve a much broader community than they were originally designed for. Climate studies, Cal/Val activities, numerical weather prediction, air quality, solar energy, ocean-colour, and natural hazard response all share the same fundamental measurements but impose different and sometimes conflicting requirements. The challenge is to provide an answer that is useful across all these applications, and that answer is not a single perfect instrument, but an ecosystem of complementary, calibrated, harmonized, and automated observing nodes, served by data infrastructures that are FAIR, API-first, and support multiple application-specific quality levels. Another core finding is related to the major gaps which currently persist over under-monitored regions like the open ocean, North Africa, the Middle East, polar regions, arid and mountain zones, and many other resource-limited environments. These gaps can only be addressed through a **measurement ecosystem** that combines reference-grade instruments, complementary low-cost sensors, marine and mobile platforms, and satellite data, all integrated through harmonized retrieval algorithms, data assimilation methods, metadata standards, and SI-traceable uncertainty frameworks, hosted on a shared software infrastructure.

Key hardware priorities identified are: automated day-night photometers with polarization capabilities; photometer–lidar supersite synergies; marine and mobile reference systems; regional calibration and traceability infrastructure; and low-maintenance autonomous stations including low-cost alternatives in under-monitored regions. Key software priorities are: operational APIs and cloud-ready data access; interoperable metadata, provenance, and uncertainty standards; automated matchup and fusion services; application-specific QC and QA procedures; and near-real-time plus delayed-mode dual data pipelines.

1. Why Columnar Aerosol Optical Properties Matter

Columnar aerosol optical properties, especially **aerosol optical depth (AOD)**, Ångström exponent, single-scattering albedo, fine and coarse mode fractions, and other products like the size distribution, are a core part of the observing system used to study climate forcing, air quality, dust and smoke transport, satellite validation, and atmospheric composition. WMO's GAW programme treats AOD as a **core aerosol variable** for long-term continuous monitoring (GCOS-244 designates AOD as an Essential Climate Variable), while consolidated networks like ACTRIS and AERONET show that modern photometer systems can deliver not only daytime AOD but also sky radiances, polarization information, night-time lunar AOD, and higher-level microphysical products.

The present observing ecosystem is already strong, but the user base has expanded well beyond climate research. As documented in D3.2, the same columnar products are now used for operational air-quality centres, numerical assimilation systems, solar-energy forecasting and nowcasting, ocean-colour missions, public health agencies, agricultural planners, aviation hazard services, and urban planning stakeholders, each with distinct quantitative requirements in terms of accuracy, uncertainty, spatial and temporal resolution, and data latency. For example, while ACTRIS explicitly frames its data services around climate and atmospheric research, satellite validation protocols consistently recognize sun photometry as the “gold standard” for column aerosol properties validation over land and ocean.

Within HARMONIA, approximately 150 scientists across Europe and other non-European countries are working to improve sun-photometric aerosol measurements and link them with applications. The scientific work produced by this community, published in a dedicated AMT/ACP special issue entitled "Sun-photometric measurements of aerosols: harmonization, comparisons, synergies, effects, and applications", provides the scientific foundation of the hardware and software evolution needs described in this report

2. The Main Communities and What They Need

The following subsections summarise the needs of each major user community and translate them into concrete hardware and software requirements, linking them to the quantitative requirements established in D3.2 and to HARMONIA scientific publications.

2.1 Climate and Atmospheric Composition Research

This community needs **long-term stability, traceability, and inter-network comparability** above all else. D3.2 identifies monthly-to-seasonal temporal resolution as sufficient but with spatial homogeneity and multi-decadal continuity as critical. Priority parameters are AOD, Ångström Exponent (AE), fine/coarse mode decomposition, and spectral single scattering albedo (SSA) with calibration traceability and consistent uncertainties as paramount quality requirements. As examples, ACTRIS emphasises that comparable methods and traceable data quality are essential because many applications require decades of time series to detect small changes confidently, while WMO-GAW similarly positions AOD as a core climate variable, stressing its traceability and long-term consistency.

Within the framework of the HARMONIA COST Action, Karanikolas et al. (2024) analyzed the differences between GAW-PFR and SKYNET AOD measurements, determining that the primary discrepancies stem from SKYNET's Improved-Langley (IL) method, which systematically underestimates the calibration constant, with only minor contributions from instrument and post-processing variations. Campanelli et al. (2024) evaluated the performance of on-site calibration methods within the SKYNET network, showing that IL method performs well at high-altitude clean sites but experiences reduced accuracy in turbid urban conditions, a limitation which is mitigated by the Cross-Improved Langley (XIL) approach. Furthermore, on-site solar disk scanning methods for determining the solid view angle (SVA) showed strong agreement with laboratory measurements. Masoom et al. (2024) evaluated how climatological NO2 assumptions affect global AERONET AOD and AE retrievals by comparing them with 7 years of co-located ground-based columnar NO2 measurements from Pandonia Global Network (PGN) Pandora spectroradiometer measurements. They found that static climatology overestimates or underestimates AOD most significantly at 380 nm in highly urbanized sites during extreme NO2 loading, which also severely distorts AE. These uncorrected biases also affected decadal AOD and AE trend analyses, illustrating the critical necessity of high-frequency ground-truth networks to resolve highly variable local emissions. Gröbner et al. (2023) demonstrated that ground-based spectroradiometer measurements of top-of-atmosphere solar spectra agreed within 1% with the TSIS-1 Hybrid Solar Reference Spectrum (HSRS), which could help to reduce its uncertainty in the ultraviolet range. Retrieved spectral AOD from these instruments showed good agreement with Langley-based calibrated instruments, satisfying WMO acceptance limits. Proving that SI-traceable spectral AOD can be successfully retrieved over an extended range of 300 to 1700 nm using laboratory-calibrated spectroradiometers instead of traditional Langley-based calibrations. Jaine et al. (2025), in the other hand, validated a compact BTS spectroradiometer for measuring total solar irradiance, showing an agreement within 0.09% of SI-traceable reference standards, highlighting the versatility of the instrument for validating radiative transfer models and potentially retrieving atmospheric gases and aerosols. Hrabčák et al. (2025) analysed a 30-year Brewer AOD dataset in Slovakia, reporting a significant long-term decrease of −0.057 ± 0.005 per decade driven by reduced regional emissions, highlighting the critical value of long, homogeneous records for detecting aerosol trends. Presentation by Amiridis (D3.1a) showed how long-term lidar-derived profiles combined with columnar aerosol products, like AOD and SSA, help to improve the understanding of vertical aerosol loading. On the other hand, Meloni (D3.1b) emphasized the importance of multi-year ground-based records for climate studies, highlighting the necessity of consistent retrieval algorithms across different measurement techniques, while Solomos (D3.1b) stressed the importance of long-term datasets for validating model simulations for studying dust-transport and climate interactions in the Mediterranean.

Hardware evolution needs

- **Better long-term radiometric stability and lower calibration/instrumental drift** (Graßl et al., 2024; Hrabčák et al., 2025; Pulimeno et al., 2026).
- **Wider spectral coverage**, especially UV to SWIR, to improve aerosol typing and absorption constraints (Gröbner et al., 2023; Jaine et al., 2025; Karanikolas et al., 2025).
- **Wider spatial coverage**, enhancing current capabilities to expand climate measurements into harsh environments such as the oceans and remote areas (García et al., 2025; Torres et al., 2025; Sánchez-Barrero et al., 2026).
- **Routine polarization capabilities** (Daskalopoulou et al., 2023).
- **Mature day-night operation** using sun/sky/lunar/stellar photometry, especially at high latitudes (Herrero del Barrio et al., 2023; Graßl et al., 2024; Román et al., 2025; Herrero-Anta et al., 2026; Pulimeno et al., 2026).
- **Stronger synergy at supersites between photometers and lidar**, since ACTRIS is explicitly moving toward higher-level products from combined profile and column observations (Tsekeri et al., 2023; González et al., 2025; Nicolae et al., 2025; Sanchez-Barrero et al., 2026).

Software evolution needs

- End-to-end uncertainty propagation, not just final-value estimates.
- Versioned reprocessing pipelines with provenance preserved at product level.
- Continuous harmonisation across AERONET, GAW-PFR, SKYNET, ACTRIS, and national networks.
- Standardised data structures and machine-readable metadata that support both immediate analysis and seamless reprocessing.
- Easy access through APIs (Application Programming Interfaces) and cloud workflows rather than file-by-file manual download. AERONET already provides a functional HTTPS GET web service, and ACTRIS now provides a FAIR-oriented portal with tools and services; that direction should continue.

2.2 Satellite Calibration/Validation Communities

Satellite teams need **reference-quality, standardised, uncertainty-characterised ground truth** with broad coverage over key aerosol and surface regimes. To meet these needs, Deliverable D3.2 specifies core requirements: AOD, SSA, AE, and vertical extinction profiles across the UV–NIR range; spatio-temporal colocation within ±10 km and ±30 minutes of satellite overpasses; near-real-time latency; comprehensive metadata; and full adherence to CEOS and WMO traceability standards. The EarthCare validation plan states that AERONET and MAN are the most widely used networks for land/coast/island and open-water validation because of standardised instrumentation and processing, well-understood uncertainties, and broad regime coverage.

A major hardware advance from the HARMONIA COST Action, is the adaptation of the CIMEL-CE318T to shipborne use by Torres et al. (2025), enabling automated and AERONET-compatible ocean observations with a GPS-based motion-compensation system, building the foundation for the development of new dedicated marine QA/QC protocols, effectively addressing the limitations of manual photometric observations at sea. Deployed aboard the RV Marion Dufresne, the instrument gathered over 25,000 day and night AOD retrievals, showing excellent agreement with ground-based standards and enabling the first-ever successful AERONET sky radiance inversions at sea. Regarding directly satellite works, Moustaka et al. (2026) enhanced dust aerosol monitoring over North Africa and the Middle East by dynamically estimating dust lidar ratios (LRs) from synergizing active (CALIPSO) and passive (MODIS and POLDER-3) satellite sensors over a 12-year period. The study revealed a significant spatial variability, with high LRs in Saharan sources and lower LRs in the Arabian Peninsula. Authors emphasized that because vast desert source regions usually lack ground stations, spaceborne observations are vital, highlighting the necessity of expanding ground coverage to these remote areas to characterize mineral dust complexity. Furthermore, Moustaka et al. (2024) evaluated the impact of replacing constant CALIPSO LRs with ground-based values from the DeLiAn database on satellite AOD and modeled shortwave Direct Radiative Effects (DREs) over the North Africa, Middle East, and Europe (NAMEE) region. Using updated ground-based LRs successfully mitigated CALIPSO’s negative AOD bias and improved surface and atmospheric DRE modeling. Validated against AERONET stations for AOD and Baseline Surface Radiation Network (BSRN) sites for downwelling surface fluxes, this work highlights the crucial role of ground-based networks in providing realistic optical inputs and validating spaceborne retrievals. On the other hand, Herrero-Anta et al. (2026) used a multi-instrument approach to analyze the exceptionally high AOD values during summer 2019 at Svalbard. Because the aerosol plumes remained trapped above the boundary layer, surface in-situ sensors missed most intrusions, proving that surface-only monitoring is structurally insufficient for long-range transport. To address this, the authors integrated active profiling, using a Raman lidar to cross-validate CALIPSO vertical extinction profiles during the complex transport events analyzed, and shipborne AOD data from the Maritime Aerosol Network (MAN) to complement land observations away from the influence of complex fjord orography. This work highlights the need for multi-instrumental campaigns and underscores the value of integrated, multi-instrumental observational coverage. Presentations from Vandenbussche (D3.1b) and Koukouli (D3.1a) highlighted metadata traceability, CEOS co-location protocols, and multi-network harmonisation as key operational needs, while Marinou's presentation (D3.1b) addressed the synergistic use of lidar and sun photometers for validating EarthCARE aerosol and cloud retrievals, underscoring the need for high vertical resolution and synchronized photometric measurements.

Hardware evolution needs

- **Expansion into under-sampled surfaces**: bright deserts, high latitudes, coastal transition zones, and open ocean (Moustaka et al., 2026; Herrero-Anta et al., 2026).
- **More maritime and shipborne capability**: MAN remains strategically important for ocean validation, and recent work on adapting standard CIMEL hardware to shipborne use points in the right direction (García et al., 2025; Torres et al., 2025; Sánchez-Barrero et al., 2026). Still needed standardized shipborne systems with improved resistance to salt, vibration, and platform motion.
- **Faster temporal sampling** to support geostationary and multi-angle satellite missions (Karanikolas et al., 2025).
- **Polarimetric and hyperspectral ground systems** to better support next-generation satellite aerosol retrievals.
- **Co-located all-sky imagers and cloud sensors** to reduce mismatch errors and improve screening (Herrero del Barrio et al., 2026).

Software evolution needs

- Automated matchup services between ground and satellite data with explicit representativeness metrics.
- Standard uncertainty budgets aligned with satellite error models.
- Near-real-time Level 1.5-style outputs for operational validation, while preserving publication-grade delayed-mode products.
- Better support for geostationary missions, including strict cloud/aerosol discrimination.
- Interoperable APIs for direct integration into cal/val dashboards and mission pipelines.

2.3 Aerosol modeling, Reanalysis and Data Assimilation

Operational forecasting centres require assimilation-ready data, well-characterized uncertainties, and dense spatial coverage accompanied by traceable metadata. Global near-real-time aerosol forecasting systems, such as the Copernicus Atmosphere Monitoring Service (CAMS Global NRT) and the Goddard Earth Observing System Forward Processing (GEOS-FP), assimilate AOD data from both satellite and ground-based networks. Similarly, long-term reanalysis products like CAMS EAC4 and MERRA-2 assimilate AOD together with in-situ observations and vertical profiling data. Beyond operational forecasting, regional models like WRF-Chem, and radiative transfer models such as libRadtran or MODTRAN depend on AOD data, optical property datasets, and mineralogy or chemical datasets for data assimilation, model evaluation, or initialization. To directly support these operational needs, deliverable D3.2 specifies as core requirements: assimilation-ready AOD and vertically resolved extinction profiles, near-real-time data delivery within 1–3 hours of measurement, vertical resolution of ≤500 m, and continuous column profiling from the surface to the tropopause.

Three HARMONIA contributions directly address the interface between observations and numerical prediction models. Solomos et al. (2023) developed METAL-WRF within the WRF-Chem framework to explicitly simulate dust mineralogy (including illite, quartz, hematite, calcite, and iron). Building on this, Spyrou et al. (2025) extended METAL-WRF by incorporating direct radiative feedbacks of dust minerals, volume-averaging eight prognostic minerals across five size bins to derive dynamic, wavelength-dependent optical parameters (e.g., SSA) for use inside the Rapid Radiative Transfer Model (RRTMG) of WRF. The results were evaluated against AERONET data during intense Mediterranean dust intrusions (March–April 2022). These two works highlight that, while operational forecasting and radiative transfer models traditionally rely on AOD data or aerosol optical properties, accurate dust modeling also requires mineral-resolved data due to the distinct properties of individual components, such as the shortwave absorption by iron or the longwave modulation by calcite, quartz, and clays. On the other hand, Zhu et al. (2026) investigated the radiative forcing (RF) of PM2.5 heavy pollution in the Bohai Rim, showing that vertical boundary layer temperature profiles frequently decouple surface aerosol concentrations from column-integrated RF, directly validating the operational requirement for continuous vertical profiling.

Using machine learning, they demonstrated that upper-level wind transport governs radiative forcing under all-sky conditions, and that all-sky pollution RF exerts an influence on regional precipitation as significant as vertical convective winds, underscoring the vital role of aerosol-radiative interactions in regional weather and precipitation forecasting models. Regarding the results of WG3, a presentation by Ades (D3.1a) highlighted the necessity of well-characterized uncertainties, metadata traceability, and temporal resolution and continuity for data assimilation into the CAMS aerosol reanalysis, emphasizing also the limitations of vertical representativeness of the data and the necessity of improved calibration alignment across different datasets. Building on these operational needs, Solomos (D3.1b) presented validation and assimilation studies stressing how the inclusion of vertical extinction profiles combined with sun photometer data improves the METAL-WRF representation of both dust transport and radiative forcing.

Hardware evolution needs

- **Denser deployment near aerosol hotspots**: wildfire corridors, dust source regions, megacities, shipping routes (García et al., 2025; Guan, et al., 2026; Herrero-Anta et al., 2026; Mateos et al., 2026; Moustaka et al., 2026).
- **Increased use of mobile and campaign-deployable systems** to fill regional gaps (Herrero-Anta et al., 2026; Mateos et al., 2026).
- **Closer coupling of photometers with lidar or ceilometer systems** to constrain vertical representativeness, since AOD alone is not enough for assimilation and forecasting. ACTRIS and GAW both highlight the value of lidar for vertical structure (Tsekeri et al., 2023; Herrero del Barrio et al., 2024; González et al., 2025; Nicolae et al., 2026; Sánchez-Barrero et al., 2026).

Software evolution needs

- Observation operators and standardised interfaces that turn AOD, Ångström exponent, and fine/coarse indicators into assimilation-ready inputs.
- Cross-platform fusion of surface in situ, columnar, lidar, and satellite data.
- Near-real-time quality-screened outputs compatible with data assimilation cycles.

2.4 Air Quality and Exposure Research Communities

Air-quality users primarily target surface PM2.5 and PM10 concentrations for exposure and health impact assessments. While column-integrated AOD is increasingly used to trace aerosol transport, detect pollution episodes, and provide regional context, translating it into accurate surface mass estimates requires precise, vertically resolved observations alongside complementary ground-based and satellite measurements. To meet these operational needs, Deliverable D3.2 specifies a requirement for near-real-time data with sub-hourly temporal resolution (≤ 1 h) and urban-scale spatial resolution (≤ 1 km).

Four different contributions stemming from the HARMONIA COST Action relate columnar and vertically resolved data with surface measurements to provide a comprehensive picture of atmospheric aerosols and their impact on air quality, radiation, and public health. Masoom et al. (2023) investigated the air quality and radiative impacts of the extreme Greek wildfires of August 2021. Peak smoke episodes generated severe AOD surges dominated by fine-mode particles, with single-scattering albedo exhibiting a decreasing spectral slope characteristic of highly absorbing biomass smoke. These events drove severe surface air-quality degradation, causing PM10 and PM2.5 concentrations to surge well above background levels alongside significant enhancements in column-integrated trace gases. Consequently, the intense optical attenuation severely reduced ground-level solar UVB irradiance, substantially lowering the noon UV index, the vitamin D effective dose, and global horizontal irradiance. On the other hand, García et al. (2026) analyzed near-source spectral radiative impacts during the exceptional wildfire on Tenerife 2023. Peak smoke episodes generated extreme AOD values indicating a heavy loading of fine-mode particles. Due to intense scattering, daily global solar irradiance fell sharply and direct-normal irradiance collapsed almost completely, while shortwave integrated radiative forcing indicated a strong net cooling effect at the surface. In situ data verified the extreme conditions at surface level, with PM10, PM2.5, and equivalent black carbon (eBC) concentrations surging well above background levels, and CO gas concentrations increasing by nearly two orders of magnitude. While Gidarakou et al. (2026) examined the optical and microphysical impacts of Greece's catastrophic 2023 wildfire season, which was characterized by extreme aerosol loading from smoke and complex Saharan dust mixtures. Optical characterization revealed strong light absorption at the visible range for fine smoke, whereas dust-smoke mixtures exhibited pronounced absorption in the ultraviolet spectrum, driving a significant reduction in ground-level UVB radiation. These effects directly coincided with severe surface air-quality degradation, as PM2.5 and PM10 concentrations surged alongside eBC and biomass-burning fractions. Correlation analyses confirmed a strong coupling between surface PM2.5 and column AOD due to fine smoke dominance, whereas coarse dust particles yielded a weaker relationship. Overall, these three works demonstrate that extreme wildfires exert profound, multi-faceted impacts on air pollution, ecosystem health, and solar energy generation, demonstrating that column-integrated optical measurements, such as spectral AOD, fine/coarse fractions, and SSA, serve as powerful indicators for mapping surface particulate levels and toxic trace gases. Finally, Proestakis et al. (2025) utilized a long-term active spaceborne lidar dataset to demonstrate that near-surface mineral dust concentrations routinely exceed international air quality guidelines across most major global cities, exposing vast urban populations to severe health risks and high attributable fractions of cardiopulmonary mortality and lung cancer. In this work, the authors combined spaceborne lidar extinction profiles with reanalysis boundary layer heights, applying a polarization-based decoupling technique to separate fine and coarse modes of dust extinction into physical mass concentrations of surface PM2.5 and PM10 proxies. This study highlights how active vertical profiling bridges the gap between traditional columnar satellite observations and ground-level exposure research, providing a vital observational tool for epidemiology in data-scarce regions lacking ground-based monitoring networks.

Hardware evolution needs

- **Co-location with PM, chemical composition, boundary-layer height, and meteorological sensors** (Masoom et al., 2023; García et al., 2026; Gidarakou et al., 2025; Proestakis et al., 2025; Guan, et al., 2026)
- **More autonomous systems near wildfire-prone regions and desert-dust source regions**

Software evolution needs

- Better fusion algorithms linking column optical properties to surface PM2.5 and exposure, with explicit uncertainty and meteorology dependence (Proestakis et al., 2025)
- Improved trace-gas correction algorithms using co-located high-frequency gas retrievals rather than climatologies (Masoom et al., 2024)
- Simpler access layers for non-specialist users in health agencies and environmental epidemiology
- Health-oriented data services: stable station identifiers, complete metadata, bias-aware gap filling, and reproducible versioning

2.5 Solar Energy Communities

The solar energy sector requires tailored atmospheric aerosol data to optimize power generation and operational logistics across both Photovoltaic (PV) and Concentrating Solar Power (CSP) facilities. Key variables, such as AOD, direct normal irradiance (DNI), and global horizontal irradiance (GHI), operating at high temporal resolutions (1–15 minutes) and fine spatial scales (100 m to 1 km), are vital for accurate power production forecasting, short-term nowcasting, and estimating dust deposition rates to mitigate soiling losses and schedule cleaning routines. Furthermore, as identified by WG3, SSA serves as a critical variable for PV plant modeling and solar forecasting across diverse atmospheric environments. Overall, the sector demands site-specific aerosol datasets delivered with high spatio-temporal resolution, supported by harmonized measurement protocols and standardized data processing workflows.

Regarding HARMONIA COST Action contributions, Papadimitriou et al. (2026) quantified the errors in PV power modeling when direct measurements of diffuse solar irradiance are unavailable. Using the Global Solar Energy Estimator (GSEE) with its integrated diffuse fraction model, the authors simulated PV generation across five European and North African sites using ground-based GHI measurements from the BSRN. They also evaluated the performance impact of using CAMS satellite radiation time-series instead of ground-based observations. The results showed that the GSEE model systematically underestimates/overestimates the diffuse fraction under heavy scattering/absorbing aerosol loads. These errors propagate into PV output simulations, impacting highly sensitive 2-axis tracking systems the most. Furthermore, utilizing CAMS satellite data rather than ground-based measurements, even when the diffuse fraction is modeled, leads to higher errors across the vast majority of sky conditions. Ultimately, this work demonstrates that neglecting site-specific aerosol ground-based metrics, such as AOD, AE, and SSA, leads to systematic errors in the estimation of the diffuse solar fraction and substantial financial risks under high-aerosol conditions. Hou et al. (2025) evaluated day-ahead AOD forecasting methods, including CAMS forecasts, AERONET persistence, and climatology, and quantified their error propagation into clear-sky DNI forecasts using radiative transfer modeling. High aerosol loads, especially at dust-dominated and mixed aerosol locations, correspond to extreme day-to-day AOD variability and significantly lower DNI predictability. While CAMS forecasts perform best at most urban-industrial locations, ground-based AERONET persistence yields lower errors at dust aerosol sites. With no current forecasting method reliably achieving a strict <5% DNI deviation, these findings reinforce the solar sector's demand for site-specific, high-resolution aerosol datasets to optimize DNI forecasting. Kouklaki et al. (2023) evaluated the impact of atmospheric aerosol variability on solar spectral irradiance (SSI) and the outdoor performance of five major PV technologies using ground-based spectroradiometer measurements in Athens, Greece. Under heavy aerosol loads, standard test conditions (STC) systematically overestimate actual solar yield, leading to output deviations of up to 45%. Wildfire smoke particles induce more severe spectral attenuation than desert dust, with high-bandgap materials like amorphous silicon (a-Si) suffering the greatest spectral mismatch and efficiency losses. Sensitivity modeling reveals that variations in SSA and AE trigger localized performance deviations of up to 15% and 12% respectively, demonstrating the value of precise, spectrally resolved aerosol measurements for outdoor PV yield forecasting. Complementary, Papachristopoulou et al. (2024) presented the operational systems SENSE2 and NextSENSE2 for high-resolution nowcasting and short-term forecasting (up to 3 hours ahead) of GHI at a ~5 km spatial scale over Europe and the Middle East and North Africa (MENA) regions. Their results demonstrated that while spatial representativeness and cloud-related uncertainties within geostationary satellite pixels represent the primary limiting factor causing GHI overestimations under cloudy skies, only a minor GHI underestimation of less than 1% arises from using CAMS-forecasted AOD under cloudless conditions, validating its reliability for clear-sky PV modeling. Furthermore, NextSENSE2's cloud motion vector (CMV) forecasting outperforms the standard persistence method by up to 20% under cloudy and transitioning skies, offering grid operators a valuable tool to predict PV ramp events and optimize real-time power dispatch. Presentations by Kazadzis, Kazantzidis, and Brito (D3.1b) emphasized the pivotal role of AOD and SSA in solar resource forecasting and PV performance modeling, highlighting how sun-photometer data can feed nowcasting systems and soiling-loss models where satellite observations lack sufficient spatiotemporal resolution. Complementing this, a presentation by Blanc (D3.1a) provided a detailed review of how aerosol variability, specifically regarding load and composition, directly impacts DNI and, consequently, PV power output.

Hardware evolution needs

- **High-frequency sampling to capture sub-hourly aerosol variability** relevant to plant operations and forecasting.
- **Spectrally resolved aerosol observations**, not only broadband AOD, to support accurate PV yield estimation (Kouklaki et al., 2023, 2026).
- **Co-location with broadband and spectral irradiance instruments** (Papadimitriou et al. 2026).
- **Expansion in arid and rapidly developing solar regions** where dust aerosols dominate uncertainty (Papadimitriou et al. 2026).

Software evolution needs

- Operational interfaces from AOD to irradiance nowcasts and forecasts (Papachristopoulou et al., 2024; Hou et al., 2025).
- Better aerosol climatologies and forecast products tailored to solar applications.

- Tools that expose aerosol type and particle size information, not just AOD (Kouklaki et al., 2023).
- Site-assessment workflows combining ground AOD, satellite products, and reanalysis consistently

2.6 Aviation

The impact of aerosols on aviation primarily concerns flight safety, specifically regarding visibility degradation and airborne hazard avoidance. Aviation agencies predominantly require detailed vertical profiles focused on hazardous aerosol layers, including mineral dust, wildfire smoke, and volcanic ash. To align with flight planning schedules, data temporal resolution must be under one hour, with seamless integration into numerical weather prediction (NWP) and early warning systems (EWS) being highly desirable. D3.2 specifies hourly updates, 1–10 km spatial resolution at airport level, latency < 1 hour, and vertical resolution < 300 m. Key aerosol parameters include backscatter and extinction profiles, aerosol typing, and layer height identification, as detailed in D3.2.

The main HARMONIA contribution addressing this topic directly, comes from the work of Barreto et al. (2026), who analyzed the 2021 Tajogaite eruption on La Palma by integrating webcam surveillance (IGN) and lidar/ceilometer profiling (AEMET-ACTRIS) to track volcanic plume heights. The ground networks showed strong agreement, while uncovering that satellite retrievals systematically underestimated layer heights and total SO2 emissions. To support aviation safety during a crisis that grounded 26% of scheduled flights (66% of which were due to ash in the airspace), the profiling network delivered continuous vertical profiles at rapid temporal resolutions (ranging from 5 seconds to 1 minute) measuring backscatter, plume heights, and depolarization for aerosol typing to distinguish spherical from non-spherical particles. Finally, ground-observed plume heights from the webcam network were integrated in real-time into VONA alerts for the Toulouse VAAC, while wind profiles from the HARMONIE-AROME NWP model were utilized to evaluate wind vector impacts on column transport and dispersion. These authors demonstrated the importance of multi-instrument synergy during this volcanic event. García et al. (2026) and Gidarakou et al. (2026) characterised extreme 2023 wildfire events using multi-sensor approaches. Additionally, WG3 contributions addressed critical aviation requirements. A presentation by Vasardani (D3.1a) examined how low vertical resolution and data delays impair civil aviation operations, showing how these gaps weakened risk management during desert dust events in Greece and Cyprus. In contrast, a presentation by Solomos (D3.1b) showed that integrating ground-based lidar extinction profiles improves dust-layer altitude forecasting, helping mitigate visibility hazards and engine wear. Lastly, Marenco (DUST-DN) stressed that columnar metrics alone cannot meet aviation needs, advocating for combined columnar and vertical profiling, citing efforts by SDS-WAS and EUMETSAT, and calling for continuous airport-based vertical sounding in vulnerable areas.

Hardware evolution needs

- **Rapidly deployable photometers and lidar-capable mobile kits** (Herrero del Barrio et al., 2024); García et al., 2025; Barreto et al., 2026; Sánchez-Barrero et al. 2026).
- **Better UV/IR spectral discrimination** for ash, dust, and smoke typing (Gröbner et al., 2023; Jaine et al., 2025; Karanikolas et al., 2025).
- **Broader network coverage near volcanoes, dust source regions, and smoke corridors** (Barreto et al., 2026; Herrero-Anta et al., 2026; Mateos et al., 2026; Moustaka et al., 2026)
- **Integration with geostationary satellite validation sites** because hazards evolve on minutes-to-hours timescales.

Software evolution needs

- Improved vertical aerosol typing and characterization (Nicolae et al., 2026).
- Strong coupling to transport and dispersion models.
- Products that explicitly support decision thresholds, alerting, and confidence estimates.

2.7 Agriculture

This sector requires aerosol observations to monitor dust and smoke intrusions affecting crop health, photosynthetically active radiation (PAR), and UV-induced plant stress. D3.2 specifies daily to seasonal forecasts with real-time alerts for extreme aerosol events (dust storms), and spatial scales from field (~1 km) to regional (~10 km).

HARMONIA studies of extreme wildfire events with strong impact in air quality (Masoom et al., 2023; García et al., 2026; and Gidarakou et al., 2026), also provide evidence of both direct and indirect aerosol impacts with agricultural relevance. On the other hand the work by Kouklaki et al. (2025), analyzed how atmospheric variability impacted surface solar radiation in Athens during the year-long ASPIRE campaign by integrating ground measurements with libRadtran radiative transfer modeling. Although the study primarily targeted general environmental, health, and modeling applications, its findings on how aerosols and clouds selectively modulate PAR (400–700 nm) compared to UV bands (UV305, UV320, and UVI) provide crucial parameters to optimize crop-usable light and monitor plant stress. Under clear skies, aerosol attenuation decreases at longer wavelengths, while dust and smoke exhibit stronger UV absorption. This creates a natural atmospheric shield that rapidly filters out harmful UV-B and mitigates plant stress during peak August aerosol loads while preserving photosynthetic light. Under all-sky conditions, broken clouds near the sun redirect diffuse light downward via multiple scattering, temporarily boosting PAR by up to 40% compared to only 17%–20% for UVI. Because these cloud enhancement events are significantly more frequent and intense for PAR than for UV radiation, these findings provide crucial parameters to optimize agricultural yields, and crop-growth forecasting. Finally, work presented by Fountoulakis (D3.1b) on UV impacts, Charalampous (D3.1b) on aerosol mapping, and Zerefos (D3.1a) on long-term UV trends highlighted that combining total solar irradiance with spectral UV observations is essential for precision agriculture.

Hardware and software evolution needs

- Real-time alerts for extreme aerosol events at field-to-regional scale.
- Integration of AOD and UV aerosol measurements with agricultural forecasting and planning systems.
- Low-cost complementary sensors for spatial densification in agricultural regions.

2.8 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. Deliverable D3.2 specifies a spatial resolution at the building-block level (~50 m), hourly temporal resolution, and a latency of under one hour, backed by integrated tools that combine remote sensing, GIS, and aerosol modeling to quantify solar resource variability and risk exposure.

Although there are no HARMONIA contributions directly dedicated to this topic, several works serve as representative use cases or offer valuable insights. For instance, mobile and personal aerosol monitoring systems, such as the Calitoo handheld photometer (García et al., 2025) and the Microtops (Guan et al., 2026), exemplify applications capable of providing observations at sub-50 m spatial resolution with low latency. Regarding other types of instrumentation, the ZEN-R52 zenith radiometer (Herrero-Anta et al., 2023) and sky-camera networks demonstrate strong potential. Specifically, González-Fernández et al. (2024) implemented a convolutional neural network (CNN)-based retrieval of shortwave solar irradiance from all-sky images using the Cloud Modification Factor (CMF), enabling ultra-short-term nowcasting for urban energy management. Similarly, Herrero del Barrio et al. (2026) introduced a novel methodology utilizing a 20-camera all-sky network in Valladolid (Spain) to map cloud height and spatial coverage across diverse cloud types and layering conditions, providing an effective framework for localized solar nowcasting. Conversely, Herrero-Anta et al. (2025) analyzed the impact of cloud-scattered light on sky-radiance measurements and its downstream effects on retrieval algorithms such as GRASP. By combining aerosol single-scattering models with libRadtran/MYSTIC (Monte Carlo code for the phYSically correct Tracing of photons In Cloudy atmospheres), they leveraged 3D Monte Carlo radiative transfer simulations to accurately estimate aerosol sky radiances under partially cloudy conditions. This framework also provides a robust methodology for modeling cloud impacts on both urban planning and energy management. Regarding specific WG3 contributions, a presentation by Brito (D3.1b) demonstrated solar cadastre development in Lisbon by integrating AOD with urban geometry datasets, yielding realistic estimates of solar energy potential across building facades and rooftops. Complementing this, Amaro (D3.1b) explored aerosol-aware irradiance modeling for urban climate risk assessments, emphasizing that higher-resolution aerosol data significantly improves solar energy forecasting, air quality monitoring, and urban heat island mitigation strategies.

Hardware and software evolution needs

- **Sub-kilometre to building-block scale aerosol data** for solar cadastre, urban energy planning, and insurance risk assessment.
- **Low-cost portable instruments validated against reference networks** (Herrero-Anta et al., 2023; García et al., 2025)
- **Cloud detection and solar irradiance retrieval from all-sky cameras** (González-Fernández et al., 2024; Herrero del Barrio et al. 2026) for very short-term solar nowcasting.
- **Real-time data services for non-specialist end users**

3. Cross-Cutting Hardware Evolution Priorities

Across all communities, the most important hardware upgrades are consistent and mutually reinforcing.

3.1 More Measurement Dimensions

Standard direct-sun AOD remains essential, but future systems should increasingly improve sky radiance measurements, polarization, lunar measurements, and broader spectral range. ACTRIS already identifies automatic sun/sky/lunar photometers and polarised radiance as state of the art.

Recent developments in radiometric and polarimetric techniques have significantly expanded aerosol characterization capabilities. Daskalopoulou et al. (2023)

demonstrated direct-sun linear polarization signatures of atmospheric dust using the SolPol polarimeter at the PANGEA observatory (Antikythera, Greece), proving that polarimetric measurements can reveal structural information, such as potential particle orientation, inaccessible to scalar photometers. Spectral coverage has similarly been extended; for example, Karanikolas et al. (2025) showed that extended observations into the shortwave infrared (SWIR) substantially improves coarse-mode aerosol retrievals. Parallel efforts have addressed critical temporal and spatial monitoring gaps. Nocturnal AOD has advanced through low-cost techniques, including starlight AOD retrieval from all-sky camera images, dramatically reducing the cost of nocturnal AOD coverage (Román et al., 2025). Lunar photometry itself helps to enhance local aerosol climatology and ensures seamless day-night continuity at stations with lunar AOD capabilities (Herrero del Barrio et al., 2023), and helped to reveal declining Arctic pollution alongside rising wildfire contributions, by enhancing the temporal coverage of AOD throughout polar darkness via the Polar-AOD program (Pulimeno et al., 2026). Finally, for remote and oceanic regions lacking state-of-the-art sun-photometer stations, alternative techniques, such as zenith-sky radiometry for aerosol property retrievals (Herrero-Anta et al., 2023), shipborne automated sun-photometers (Torres et al., 2025; Sánchez-Barrero et al., 2026), and validated low-cost handheld devices like Calitoo (García et al., 2025), provide reliable observation coverage.

3.2 Calibration Ecosystems

The utility of columnar aerosol optical properties depends fundamentally on rigorous calibration traceability. Consequently, major international frameworks, including WMO, AERONET, and ACTRIS, position standardized calibration and QC/QA protocols at the core of network data integrity. This necessity supports the expansion of world and regional calibration centers, robust transfer standards, and regular intercomparison campaigns. Karanikolas et al. (2024) identified calibration as the dominant source of inter-network AOD differences. Gröbner et al. (2023) demonstrated that SI-traceable spectral AOD can be successfully retrieved over an extended range of 300 to 1700 nm using laboratory-calibrated spectroradiometers. Campanelli et al. (2024) showed that on-site calibration performed well at pristine, high-altitude sites by continuously monitoring instrumental drift, whereas performance degraded under turbid urban conditions. Meanwhile, Jaine et al. (2025) validated a compact BTS spectroradiometer for measuring total solar irradiance, demonstrating excellent agreement with SI-traceable reference standards and highlighting the versatility of the instrument for validating radiative transfer models as well as potential atmospheric gas and aerosol retrievals.

3.3 Stronger Profile–Column Synergy

Key user communities increasingly demand vertically resolved profile products rather than total column AOD alone. ACTRIS is addressing this need by developing synergized higher-level products that combine lidar and photometer observations, leveraging the distinct spatial and temporal resolutions of both systems for comprehensive aerosol characterization. Multiple HARMONIA studies demonstrate the power of this synergetic approach: Sánchez-Barrero et al. (2026) coupled photometer and lidar observations during the TRANSAMA marine campaign to characterize vertical aerosol distribution; Herrero-Anta et al. (2026) integrated photometers, airborne in situ sensors, and lidar to analyze the extreme 2019 Svalbard AOD event; and Barreto et al. (2026) combined lidar and photometry during the Tajogaite eruption to track plume altitude and highlight limitations in satellite-derived SO2 and height retrievals. Deliverable D3.2 explicitly targets vertical resolutions ≤ 500 m with full column coverage as essential inputs for atmospheric modeling and reanalysis. Ultimately, these findings confirm that synergistic observational approaches are scientifically superior and operationally necessary for both characterizing extreme events, and aerosol climatologies (Massom et al., 2023; García et al., 2026; Girdakou et al., 2026; Nicolae et al., 2026).

3.4 More Autonomous and Resilient Deployment

The user base increasingly needs observations in deserts, polar zones, oceans, wildfire regions, and low-resource areas. D3.2 documented coverage gaps over developing countries, urban microclimates, coastal zones, and high-dust regions such as North Africa and the Middle East. The HARMONIA community has addressed this through mobile hardware development (Torres et al., 2025; Sánchez-Barrero et al., 2026) exploration of low-cost alternatives (Herrero-Anta et al., 2023; González-Fernández et al., 2024; Román et al., 2025; García et al., 2025), and use of satellite data (Moustaka et al., 2024, 2026).

4. Cross-Cutting Software Evolution Priorities

Modern observation networks rely as much on robust software processing as on physical instrumentation. D3.2 highlighted that user communities consistently demand real-time data access, explicit uncertainty reporting, standardized formats, complete metadata traceability, and seamless system interoperability.

4.1 From File Archives to Data Services

AERONET's web service and ACTRIS's FAIR portals show the transition from manual download toward machine-accessible data services. D3.2 found that current latency (hours to weeks for validated data) is too high for forecasting, assimilation, and health risk communication. Future systems should provide stable APIs, cloud-native formats, subsetting, and workflow-ready systems.

4.2 Uncertainty Metadata to Products

Data should carry algorithm version, calibration lineage, uncertainty components, complete and traceable metadata, and QC/QA logic in machine-readable form. For example, within ACTRIS, the Centre for Aerosol Remote Sensing (CARS) coordinates harmonized procedures for instrument operation, calibration, and quality assurance to provide reliable, long-term datasets of column- and profile-level aerosol optical properties. To support robust climatological analyses and model evaluations, ACTRIS emphasizes metrological traceability, standardization, and data versioning as core data-centre functions. Recent research coordinated under the HARMONIA Action has quantified and studied several critical sources of aerosol retrieval uncertainty. These include on-site calibration discrepancies between different instrument networks (Karanikolas et al., 2024; Campanelli et al., 2024) and ultraviolet-visible spectral biases arising from the high spatiotemporal variability of atmospheric NO2 corrections (Masoom et al., 2024), and SI-traceable calibration techniques (Gröbner et al., 2023; Janine et al., 2025).

4.3 Fused Products

Users increasingly require integrated, high-end synergistic products that combine column-integrated properties with vertical profiles, ground-based observations with satellite measurements, and observational data with regional models. Within ACTRIS, the Aerosol Remote Sensing (ARES) framework explicitly highlights the development and validation of synergistic retrieval algorithms. For example, during the EARLINET/ACTRIS COVID-19 campaign, the community evaluated the network-level application of the GRASP/GARRLiC synergistic inversion algorithm, which combines ground-based sun photometer and lidar profiles to retrieve vertically-resolved optical properties (Tsekeri et al., 2023). Advanced classification algorithms are also expanding beyond traditional inversions to identify aerosol origins from vertically resolved synergistic profiles. For example, the NATALI code (Nicolae et al., 2026) feeds multi-wavelength Raman lidar profiles—backscatter, extinction, and depolarization—into neural networks for automated layer classification. Combined with columnar photometer measurements, this approach provides a powerful tool for characterizing aerosol optics, occurrence, and source attribution across the troposphere.. Similarly, shipborne campaigns such as TRANSAMA have demonstrated the utility of fusing ground-level micro-pulse lidar profiles with automated photometer measurements to study marine boundary layer variability over oceans (Sánchez-Barrero et al., 2026). Over wider scales, spaceborne multi-sensor synergy is achieved by combining active spaceborne lidar profiling (CALIOP) with passive satellite observations under the A-Train constellation to retrieve regionally representative dust optical properties and evaluate shortwave radiative effects (Moustaka et al. 2024, 2026). Under extreme wildfire events, integrating ground-based sun-sky-lunar photometers, multi-wavelength Raman lidars, satellite observations, and radiative transfer models has proven essential to characterize the microphysical and radiative impacts of transported smoke plumes (Masoom et al., 2023; García et al., 2026; and Gidarakou et al., 2026).

Amiridis et al. (2024) also outlined several overarching challenges to enhancing our understanding of aerosol-radiation-cloud interactions. These challenges include upgrading and expanding ground-based monitoring infrastructures through global and European network initiatives. Additionally, systematic aircraft and unmanned aerial vehicle (UAV) in situ measurements of aerosol microphysical and chemical properties, combined with concurrent meteorology, are needed to facilitate closure studies of major air masses. Finally, future efforts must focus on integrating satellite observations, suborbital measurements, and modeling using advanced data assimilation techniques.

The study presented by Masoom et al. (2026) demonstrated the value of integrating ground-based remote sensing, in situ observations, satellite retrievals and atmospheric reanalyses to achieve a comprehensive characterization of extreme biomass-burning aerosols while revealing the limitations of satellite-only products during such events.

4.4 Application-Specific QA

Climate users need delayed-mode data; forecasting users need low-latency robust screening; health users need continuity and stable metadata; hazard users need event handling and anomaly tolerance. AERONET's separation of Level 1.5 (operational) and Level 2.0 (publication-grade) products is a practical model. Crucially, any integrated measurement ecosystem that includes low-cost sensors alongside reference instruments must incorporate explicit quality labelling that indicates the traceability and uncertainty class of each data stream, so that end users can select the appropriate data for their application.

4.5 From Algorithms to Community-Extended Software

Open, versioned reference implementations are increasingly necessary to validate and adopt new retrieval methods, uncertainty models, and matchup frameworks across monitoring networks. Within the HARMONIA framework, this open approach is exemplified by the GRASP algorithm, which serves as a common retrieval engine capable of processing diverse observational platforms, including photometers, zenith sky radiometers, lidar systems, and low-cost sensors.

5. Highest-Priority Investments

5.1 Hardware Priorities

- **Automated sun/sky/lunar/stellar photometers with polarization** options for day-night, higher-information-content measurements.
- **Photometer–lidar supersite combinations** for vertically constrained high-end aerosol products.
- **Marine and mobile reference systems to expand observation coverage into remote and extreme environments** (e.g., oceans, deserts, wildfire events, and polar regions).
- **Regional calibration and transfer-standard capacity to support network growth without losing traceability**.
- **Validated complementary instruments**: Calibrated zenith radiometers, all-sky cameras in photometric mode, and adapted shipborne systems for targeted deployment in observational gap regions.
- **Low-cost sensor evaluation and standardisation**: Continued scientific validation of citizen-science and ultra-low-cost sensors instruments against reference standards, with transparent documentation of uncertainty and application scope.

5.2 Software Priorities

- **Operational APIs and cloud-ready access** across all major networks.
- **Interoperable metadata, provenance, and uncertainty standards**, including quality-level labelling, for multi-tier data.
- **Automated matchup and fusion services** for satellite, model, and multi-sensor applications.
- **Application-specific QA/QC profiles** for climate, air-quality, and aviation.
- **Near-real-time plus delayed-mode dual pipelines** so operational utility does not compromise climate-grade archives.

- **AI or Machine learning–augmented retrieval** for faster processing and integration of data from complementary sensors.
- **Observational gap-mapping services**: Dynamic tools that map current coverage and guide optimal deployment of new instruments.

6. The Measurement Ecosystem: Low-Cost Sensors and Filling Observational Gaps

One of the most important ideas developed across the years of HARMONIA activity, and consolidated through the WG4 meetings in Davos 2025 and Valladolid 2026, is that reference-grade monitoring networks alone cannot address all the challenges facing today's aerosol observing systems. A fundamental shift in perspective is needed: from thinking about independent networks operating different reference instruments, to thinking about a fully integrated **measurement ecosystem**—an integrated multi-level observing architecture where reference-grade instruments, low-cost sensors, and satellite platforms operate synergistically, each addressing specific spatial, temporal, or operational gaps.

6.1 The Observational Gap Problem

Major observational gaps remain in the global aerosol monitoring network. These gaps are not random, they are concentrated in precisely the regions that matter most for key applications:

- **North Africa and the Sahel**: The world's most active dust source region, where mineral dust dominates aerosol forcing, air quality, and climate effects. AERONET stations are sparse, making it impossible to characterise the spatial variability of dust emission, transport, and deposition at the temporal and spatial scales required for forecasting and satellite validation.
- **Open seas and coastal shipping routes**: Critical for ocean-colour atmospheric correction, marine boundary layer aerosol characterisation, and validation of satellite retrievals over water. Despite the promising development of marine-based photometry, the reliance on

ships-of-opportunity and research vessel campaigns provides only episodic coverage.

- **Polar regions**: Aerosol monitoring during the polar night requires night-capable instrumentation and extreme environmental robustness. These capabilities are becoming critical for climate monitoring, given the rising frequency of wildfire-origin smoke plumes and unusual aerosol events at high latitudes.
- **Remote and resource-limited environments**: Large parts of Sub-Saharan Africa, Central Asia, the Amazon, and Oceania lack the infrastructure, technical capacity, and funding to operate and maintain reference photometers continuously. Yet these regions are critical for global aerosol budgets.
- **Urban and peri-urban environments in rapidly developing regions** where dense spatial coverage is needed to characterise the horizontal variability of pollution aerosols for health studies and air quality management, but the economics of reference-grade instruments make dense networks prohibitive.

D3.2 and HARMONIA contributions explicitly documents major coverage gaps: North Africa and the Sahel (most active dust source region with sparse aerosol monitoring coverage), open ocean and maritime routes, polar regions (where night-time monitoring is critical), remote and resource-limited environments, and dense urban environments in rapidly developing regions. Moustaka et al. (2026) demonstrated this gap directly for North Africa and the Middle East. Pulimeno et al. (2026) showed increasing wildfire aerosol contributions to polar regions. Both regions are precise examples where current reference network density is insufficient.

6.2 Why Reference Networks Alone Cannot Solve This

Reference-grade sun photometers like the CIMEL, the backbone of AERONET and ACTRIS, are excellent instruments. They deliver well-characterised, inter-network-comparable AOD with uncertainty typically below 0.01–0.02 when properly calibrated. But they have inherent limitations for gap-filling:

- **Cost**: A reference grade photometer (RGP) with full calibration infrastructure costs tens of thousands of euros per site, plus recurring calibration, maintenance, and operator costs. Deploying hundreds of additional sites in under-sampled regions requires sustained investment at a scale that current funding frameworks cannot support.
- **Maintenance complexity**: RGP instruments require regular cleaning, filter checks, calibration, and expert operators. In remote or resource-limited environments, this is a recurring challenge that limits data continuity.
- **Environmental constraints**: Marine environments, desert sites, and polar locations present particular challenges for delicate optical systems. Standard configurations were not designed for salt spray, extreme temperature cycles, or harsh weather conditions.
- **Fixed deployment**: Reference photometers are by design installed at fixed, well-characterised sites. They cannot easily follow aerosol events, support field campaigns, or provide spatial mapping within a region.

This is not a criticism of reference networks, it is a statement of scope. The scientific community has spent decades building and validating reference networks like AERONET, GAW-PFR, and SKYNET. But to address the observational gaps, a complementary strategy is needed.

6.3 The Complementary Approach: A Hierarchy of Sensors

The measurement ecosystem approach recognises that different measurement needs can be served by different instrument classes, and that scientific value is generated by their intelligent combination rather than by any single instrument type alone. Three complementary levels can be identified:

Level 1 — Reference instruments (CIMEL/AERONET, GAW-PFR, POM/SKYNET): They are the backbone of the system, providing high quality, long-term, inter-network-comparable measurements at a limited number of well-chosen sites. HARMONIA's calibration harmonisation work (Gröbner et al., 2023; Campanelli et al., 2024; Karanikolas et al., 2024) is specifically aimed at maximising the value of this layer.

Level 2 — Validated complementary instruments: (e.g., shipborne CIMEL, calibrated zenith radiometers, all-sky cameras): They are instruments that are either purpose-adapted for specific environments or simplified for broader deployment, but validated against Level 1 references. They extend spatial and temporal coverage without claiming full reference-grade traceability at every deployment. Key HARMONIA contributions at this level include:

- *ZEN-R52 zenith radiometer* (Herrero-Anta et al., 2023): A simple, low-cost zenith-pointing radiometer whose signal, processed with GRASP inversion, can retrieve AOD and aerosol volume concentrations (total, fine, and coarse modes) comparable to photometric measurements. The instrument requires no sun-tracking mechanism, dramatically reducing complexity and cost, and is well-suited to remote or unmanned deployments.
- *Calitoo* (García et al., 2025): This low-cost instrument can become a valuable component of a monitoring strategy, provided that it demonstrates sufficient data quality to meet the required performance targets through comprehensive evaluation and validation against independent reference instrumentation. A 5-year evaluation demonstrated that the low-cost Calitoo sun photometer provides AOD measurements in good agreement with AERONET (R = 0.727–0.917; mean bias = -0.030 to -0.001), supporting its suitability for aerosol monitoring in remote marine regions.
- *All-sky cameras for nighttime AOD* (Román et al., 2025): A novel method to extract starlight signals from standard all-sky cameras and retrieve AOD at nighttime, validated against lunar photometry. All-sky cameras are increasingly deployed for cloud monitoring at meteorological stations worldwide at a fraction of the cost of stellar photometers. Repurposing them for aerosol retrieval has the potential to dramatically expand nighttime AOD coverage at minimal additional cost.
- *All-sky cameras in cloud-sensing mode* (González-Fernández et al., 2024): All-sky cameras are increasingly deployed at meteorological and aerosol stations worldwide at a fraction of the cost of dedicated photometers. A CNN-based model trained on over 237,000 sky images has demonstrated the retrieval of solar shortwave irradiance via Cloud Modification Factor estimation, enabling very short-term solar nowcasting.

- *Shipborne CIMEL-318T* (Torres et al., 2025): A standard CIMEL adapted for operation on a moving vessel through a GPS-based motion-compensation system achieving AERONET-compatible data quality and aerosol inversions over three years in the Indian Ocean aboard the Marion Dufresne. This demonstrates that the marine gap can be addressed through hardware adaptation rather than entirely new instrument development.

Level 3 — Citizen-science and ultra-low-cost sensors (e.g., Calitoo handheld photometer, PM2.5 low-cost sensors, smartphone-based instruments): The widest-deployment tier, intended primarily for spatial coverage, education, and event detection rather than for scientific retrievals requiring full traceability. Their value lies in density and accessibility. For this level, the key requirements are: (a) honest documentation of uncertainty and known limitations; (b) comparison against reference instruments in controlled conditions; (c) integration into frameworks that clearly flag data quality class.

6.4 The Integration Challenge: Low-Cost Does Not Mean Low-Science

A central message reinforced at the WG4 Valladolid meeting is that "low-cost does not mean low-science". The scientific usefulness of Level 2 and Level 3 instruments depends critically on the same properties that make reference instruments valuable: calibration, quality control, uncertainty characterisation, harmonisation, and metadata. Deploying a low-cost sensor without understanding its uncertainty, drift characteristics, and environmental sensitivities does not fill the observational gap, it creates an illusion of coverage that can mislead downstream users.

The HARMONIA approach to low-cost sensor integration therefore insists on:

- **Explicit uncertainty characterisation**: What is the expected uncertainty of this instrument type, under what conditions, compared to what reference?
- **Controlled comparisons**: Every new instrument class deployed within the ecosystem should be compared against Level 1 reference instruments in co-located campaigns before operational deployment.

- **Transparent quality labelling**: Data products should clearly indicate which measurement level they come from and carry appropriate uncertainty metadata.
- **Gap-filling purpose**, not replacement: The goal is to fill spatial and temporal gaps where reference instruments are not present, not to substitute them where they are.
- **Openness about limitations**: Which applications can this data be used for, and which cannot? A Calitoo reading during a Saharan dust event is scientifically valuable for tracking dust transport but is not meant to be used for calibration transfer.

The ZEN-R52 study by Herrero-Anta et al. (2023) exemplifies this approach: the instrument was rigorously validated against reference photometers using a dedicated calibration methodology based on radiative transfer simulations, the uncertainty of the retrieved products was quantified, and specific applications (AOD and volume concentration in remote areas) were defined for which the instrument is appropriate.

6.5 A Strategic Vision: From AOD Stations to an Aerosol Observing Ecosystem

The strategic vision that emerges from HARMONIA is a shift from a network of individually operated AOD stations to an integrated aerosol observing ecosystem with the following characteristics:

The HARMONIA Aerosol Observing Ecosystem Vision
Backbone layer: ~500–1000 reference sites (AERONET, GAW-PFR, SKYNET) providing high-quality, long-term, inter-network-harmonised AOD. HARMONIA's harmonisation work is specifically aimed at maximising the value of this layer.
Coverage layer: Several thousand validated complementary measurement nodes using Level 2 instruments (shipborne systems, calibrated low-cost photometers, and all-sky cameras) deployed in currently under-sampled regions and environments. These nodes are calibrated against the backbone layer and report data with explicit uncertainty metadata.
Event and campaign layer: Mobile reference systems, rapidly deployable multi-instrument platforms, and airborne/drone-borne systems for targeted campaigns during events

(volcanic eruptions, extreme dust events, wildfires) and for ground-truth of satellite validation campaigns.

Integration layer: Common data formats, APIs, and fusion software (including ML approaches) that combine all levels into analysis-ready products with quality metadata, making the ecosystem as a whole greater than the sum of its parts.

This ecosystem approach does not require a revolution; it requires a deliberate evolution of what already exists. The reference networks are already strong. The complementary instruments are already being validated. The fusion software (GRASP, ML methods) is already being developed. What is needed is a coordinated framework, exactly the type of activity that HARMONIA has been building, that connects these elements into a coherent, community-maintained observing system with shared quality standards and data infrastructure.

7. Gaps and Challenges

Based on D3.2 and the HARMONIA scientific publications, the following cross-cutting gaps have been identified:

- **Spatial and temporal coverage gaps**. Despite global progress in sun photometric aerosol monitoring, significant spatial coverage gaps remain, particularly over developing countries, oceans, and urban microclimates. 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 polar winter. D3.1b presentations by Brito, Kazantzidis, and Solomos illustrated how this limits PV yield prediction, dust event monitoring, and regional climate analysis.
- **Spectral range gaps (UV/IR)**. Most current networks are optimised for visible and near-infrared wavelengths. The UV range is essential for public health, UV Index modelling, and both desert dust and brown carbon characterization, while the IR is critical for detecting coarse-mode aerosols and satellite Cal/Val procedures. Few instruments have stable, accurate calibration in these bands. Presentations by Fountoulakis (D3.1b) and Meloni and Marinou (D3.1b) stressed that current spectral limitations restrict

multi-sectoral use. Karanikolas et al. (2025) demonstrated the significant retrieval improvement from extending spectral coverage to the SWIR.

- **Calibration and harmonisation**. Inter-network disparities in calibration procedures, reference standards, and retrieval algorithms complicate data merging. Kazadzis (D3.1a) and Vandenbussche (D3.1b) addressed discrepancies in SSA and AOD retrievals between AERONET and other networks. Karanikolas et al. (2024) identified calibration as the dominant source of GAW-PFR vs. SKYNET differences. Lack of SI-traceable standards and centralised cross-network calibration campaigns are key obstacles to interoperability.
- **Real-time accessibility and uncertainty reporting**. Many communities require near-real-time aerosol products with clear uncertainty estimates. Current latency ranges from a few hours (AERONET Level 1.5) to several months (validated Level 2). In D3.1a and D3.1b, Ades, Marinou, and Charalampous stressed that validated data latency is too high for forecasting, assimilation, and health risk communication. Few products offer transparent, uncertainty estimates.
- **Night-time monitoring**. Passive remote sensing of aerosols is limited to daytime. Lunar and stellar photometry and all-sky camera-based approaches (Herrero del Barrio et al., 2023; Graßl et al., 2024; Román et al., 2025) are emerging, but this field remains nascent with higher uncertainties than solar measurements (Pulimeno et al., 2026).

8. Strategic Recommendations

Building on D3.2 and the HARMONIA scientific evidence, the following strategic recommendations are proposed:

- **Network expansion**. Expand the spatial density of sun photometer installations, particularly in coastal, desert, and mountainous regions. Deploy compact, autonomous photometers in under-monitored zones, and complement reference installations with validated Level 2 instruments in regions where reference-grade systems cannot be sustained. WG3 presentations by Brito, Charalampous, and Kazantzidis, as well as training activities in Izaña, highlighted the operational benefits of deploying compact, autonomous photometers in under-monitored zones.

- **Data integration and interoperability**. Interoperability across AERONET, SKYNET, and GAW-PFR remains a central need for data assimilation, satellite validation, and modelling. Harmonise retrieval algorithms, metadata standards, and uncertainty quantification in line with FAIR data principles. Transition from file-based archives to API-first data services with explicit quality labelling by measurement tier.
- **Calibration infrastructure**. Establish more regional calibration centres and transfer-standard campaigns to maintain traceability as networks expand. Invest in on-site calibration monitoring that continuously tracks instrument drift (Campanelli et al., 2024). Link calibration protocols to SI-traceable standards (Gröbner et al., 2023; Jaine et al., 2025).
- **Training, capacity building, and summer schools**. The summer schools (Sorbetto, 2023; Sky Over Berlin, 2024; Above the Clouds, Izaña, 2025) proved critical for knowledge transfer across research generations. It is recommended that these activities be institutionalised not only within HARMONIA, but also within partner networks, with expanded participation and sector-specific modules for energy, health, and satellite communities.
- **Alignment with global initiatives**. All recommendations should align with GCOS Implementation Plan 2022 (GCOS-244), WMO GAW guidelines, Horizon Europe Earth observation priorities, ACTRIS, and EarthCARE validation frameworks. Strategic alignment ensures that European efforts remain interoperable, policy-relevant, and globally visible.

9. Summary of User Requirements

The following table consolidates the key aerosol measurement requirements across major user sectors, as identified through HARMONIA WG3 activities (D3.2) and confirmed by HARMONIA scientific publications.

User Sector	Key Measurement Needs	Spatial Res.	Temporal Res.	Latency	Priority Parameters	HARMONIA References

Solar Energy	AOD, SSA, AE, DNI, GHI	100 m–1 km	1–15 min	< 1 h	AOD and SSA	Hou et al.,2025; Papadimitriou et al.,2026; Kouklaki et al.,2023; Papachristopoulou et al.,2024
Satellite Validation	AOD, SSA, AE, vertical profiles	≤10km (co-loc.)	±30min overpass	Near-synch.	AOD and AE.	Moustaka et al. 2024; Torres et al.,2025; Sánchez-Barrero et al.,2026
Atm. Modeling / Reanalysis	AOD, extinction profile, SSA, AE	≤10 km	Hourly–3-hourly	< 3 h	AOD, SSA, and vertical profiles.	Solomos et al.,2023; Spyrou et al.,2025; Zhu et al. 2026.
Climate Science	AOD, SSA, AE, inversion products.	Regional–global	Monthly–seasonal	Not critical	AOD, SSA, and AE.	Gröbner et al.,2023; Karanikolas et al.,2025; Hrabčák et al.,2025.
Air Quality	AOD, AE, PM proxy, UV Index	≤1 km	Sub-hourly	< 1 h	AOD, PM proxy	Masoom et al.,2023; Gidarakou et al.,2026; Proestakis et al.,2025
Aviation	Backscatter, extinction profiles, aerosol type	1–10 km (airport)	Hourly	< 1 h	Extinction profiles, aerosol types	Barreto et al.,2026
Agriculture	AOD, UV, PAR	1–10 km	Daily–weekly	< 1 day	AOD and PAR	García et al.,2026; Gidarakou et al.,2026; Masoom et al.,2023, Kouklaki et al.,2025
Urban Planning/ Emerging Use Cases	AOD, DNI, GHI, sky obstruction	50–100 m	Hourly	< 1 h	DNI, GHI, and sky obstruction	Herrero-Anta et al.,2025;; González-Fernández et al.,2024; Herrero del Barrio et al., 2026.

10. Conclusion

The biggest shift for aerosol columnar optical-property observing systems is that they are no longer serving only one community. As established in D3.2, the same core measurements now support climate science, satellite Cal/Val, atmospheric modeling and reanalysis, solar energy, air quality, agriculture, urban planning, and aviation communities. Because of that, the next generation should evolve in two directions simultaneously: **richer hardware** (more dimensions, better calibration, extended deployment environments) and **more service-oriented software** (FAIR data services, uncertainty-aware, multi-tier integration).

A central insight developed through HARMONIA is the **measurement ecosystem concept**: a structured combination of reference-grade instruments, validated complementary sensors, and satellite data, integrated through common quality frameworks. Reference networks provide the irreplaceable calibration and long-term continuity backbone. Validated complementary instruments — from adapted shipborne CIMEL systems to calibrated handheld photometers — extend coverage to the regions and environments that reference networks cannot reach. The combination, not any individual element, will address the observational gaps over North Africa, the open ocean, polar regions, and resource-limited environments that currently limit both science and societal applications.

In practice, that means moving from "AOD stations" to **multi-dimensional aerosol reference nodes**: calibrated, automated, day-night capable, polarization-aware, linked to lidar where possible, and delivered through FAIR, API-first, software systems. That is the most efficient path to meet the diverse needs of the scientific and operational communities using aerosol data over the next decade.

The WG4 meetings in Davos and Valladolid demonstrated that this vision is achievable through genuine collaboration between the scientific community, instrument manufacturers, and end users. The HARMONIA scientific publications provide the empirical evidence that calibration traceability, network harmonisation, extended measurement dimensions, and synergistic observing approaches are scientifically validated and in many cases already demonstrated. The task ahead is to translate this evidence into concrete hardware design requirements, software standards, procurement guidance, and deployment strategies for the next generation of aerosol monitoring systems — building, together, the integrated observing ecosystem that the challenge demands.

11. WG4-Davos. Main Topics of the Workshop, Issues Discussed and Aspects for Improvement

- Scientists presented their instruments and the main issues they are currently facing with the aim of showing manufacturers aspects for improvement and guiding them towards the creation of better instruments.
- On the other hand, insights from instrument manufacturers and companies developing algorithms such as GRASP were discussed.
- Some successful science-manufacturers collaborations were shown in order to encourage both interested parties.
- Presented new developments in measurement characterisation and instrument calibration from the scientific community.
- Companies encouraged scientists to rent their instruments to try them before a purchase, due to the high prices.
- Discussed potential synergies in instrument advancements, not only between scientists-companies but also between researchers from different networks.
- Reflected the perspectives of instrument users through a dedicated questionnaire, which allowed companies to understand their users' main requests in a simple way.

12. WG4-Valladolid. Wrap-Up Discussion

As a brief summary, the meeting was structured around several complementary topics, all of which can be considered combined approaches for aerosol observations, including low-cost instrumentation, practical applications, emerging technologies, and synergistic techniques. Together, they constitute a very interesting set of tools that perfectly complement those presented during our previous WG4 meeting in Davos. This reflects an important idea: reference-grade monitors alone are not able to address all the challenges that today's aerosol observing systems face.

The first session introduced All-Sky Cameras, covering both the scientific perspective and the manufacturer's point of view. This technique clearly emerges as a powerful complement to Sun-Moon-Sky photometers within the current climate observing system. González-Fernández et al. (2024) demonstrated CNN-based retrieval of solar shortwave irradiance from all-sky camera images. Román et al. (2025) showed nighttime AOD retrieval from starlight signals in all-sky images.

Moving to applications, we discussed the importance of accurate aerosol forecasts and the assessment of both the direct and indirect aerosol effects for solar energy applications. Hou et al. (2025) and Papadimitriou et al. (2026) directly demonstrated the link between AOD quality and solar energy forecasting accuracy.

Several low-cost sensors were then presented, highlighting their potential to extend the spatial coverage of existing observation networks. We also learned from the experience of two European institutions working to expand PM measurements in key mineral dust source regions across Africa. These presentations emphasised the major societal and public health impacts of dust and sand storms on a global scale. Providing timely and reliable information to society is essential for anticipating these events and supporting efficient Early Warning Systems.

Other low-cost instruments, such as the ZEN radiometer (Herrero-Anta et al., 2023) and the Calitoo handheld photometer, also demonstrated their potential to complement reference photometers such as the Cimel, particularly in remote locations where deploying more sophisticated instrumentation is challenging.

Regarding emerging technologies, we were introduced to an interferometric aerosol monitor as an alternative approach for in situ aerosol measurements. In addition, a modified Cimel instrument designed for shipborne observations was presented (Torres et al., 2025). This represents a significant achievement, involving not only an innovative system to compensate for ship motion but also the development of dedicated QA/QC protocols specifically adapted to the marine environment.

Finally, synergistic approaches played a central role throughout the meeting. By combining different measurement techniques, these approaches can provide additional products that cannot be retrieved by individual instruments alone while also compensating for the limitations inherent to each method. The idea is moving towards a synergistic network of co-located multi-instrument observations — something like a hybrid measurement ecosystem.

All these developments are particularly relevant in the context of HARMONIA, where they could play a key role in the future co-design of the next generation of aerosol observing systems, helping to: (1) improve global observational coverage; (2) strengthen the integration of observations with models and satellite information; and (3) enhance societal relevance and better address end-user needs.

Strategic Framing for Future Industry Talks

This session prompted a broader reflection on how to frame industry talks (Tenum/Calitoo and similar low-cost manufacturers) in future editions of the WG4 meeting so that they contribute more directly to HARMONIA's objectives, rather than reading as commercial or purely technical presentations. Five themes were identified as a more useful structure for these sessions:

- **Observational gap**: which concrete gap does the instrument address — e.g. lack of AOD coverage in North Africa, the practical impossibility of deploying dense Cimel/AERONET-type networks, mobile or citizen-science measurement needs, capacity building — framing the instrument as part of a wider observational strategy rather than a standalone low-cost gadget
- **Quality and traceability**: an open, honest discussion of calibration approach, temporal stability, expected uncertainty, comparisons against AERONET/Cimel, known limitations, and environmental sensitivities — since low-cost should not be equated with low-science
- **Complementarity rather than replacement**: the value such instruments add without substituting reference-grade instrumentation — e.g. spatial densification, intensive campaigns, maritime observations, regional satellite validation, extreme events, gap-filling, and support to PV forecasting
- **Integration with GRASP and hybrid platforms**: how the instrument's data (formats, APIs, metadata, automation) can feed into synergistic, multi-platform retrievals alongside lidar, satellite, and other observing systems, rather than being considered only as a hardware product

- **Future roadmap**: manufacturer plans for miniaturisation, autonomy, automated AI-based QC, multi-spectral capability, connectivity/cloud integration, and cost reduction, as a basis for dialogue between industry and the scientific community

The suggested core message is that the aerosol observing ecosystem of the future will likely rely not on a single perfect instrument, but on the intelligent integration of complementary, scalable and accessible technologies capable of filling the major observational gaps that persist globally (North Africa, oceans, remote and resource-limited regions) — in line with WG4's industry-engagement objective and WG3's focus on end-user applicability.

Connecting to the HARMONIA Framing

Beyond the specific outcomes of each talk, the discussion reinforced a broader framing worth carrying forward. Major observational gaps remain, particularly over North Africa, oceans, remote areas and resource-limited regions — precisely the regions that matter most for dust transport, climate forcing, air quality and PV production. Reference networks such as ACTRIS and AERONET remain essential but cannot resolve this spatial problem alone; this is exactly why complementary, portable, low-cost and autonomous observing platforms are needed.

The challenge ahead is no longer only about measurement accuracy, but about integration: the future of aerosol observing will most likely rely on the intelligent combination of multiple, partial observations — satellites, lidar, photometers, all-sky cameras, PM sensors, shipborne systems and radiative measurements — brought together through frameworks such as GRASP.

At the same time, low-cost does not mean low-science: the scientific usefulness of these systems depends on calibration, quality control, uncertainty characterisation, harmonisation and metadata, and this discussion should remain honest and rigorous rather than purely promotional. Ultimately, the value of meetings like this one lies in building bridges between science, industry and end users — moving beyond companies simply showcasing products, towards genuine co-design informed by user needs, scientific priorities and operational applicability.

In short: this meeting was not about replacing reference instrumentation, but about understanding how complementary, emerging and more accessible technologies can strengthen the global aerosol observing system and help address the observational gaps that still limit both science and its applications — building, together, the next generation of aerosol observing systems.

13. References

Amiridis, V., et al.: Natural Aerosols, Gaseous Precursors and Their Impacts in Greece: A Review from the Remote Sensing Perspective. Atmosphere, 15, 753, https://doi.org/10.3390/atmos15070753, 2024.

Barreto, A., et al.: Volcanic plume height during the 2021 Tajogaite eruption (La Palma). AMT, 19, 1385–1406, https://doi.org/10.5194/amt-19-1385-2026, 2026.

Campanelli, M., et al.: Evaluation of on-site calibration procedures for SKYNET Prede POM sun-sky photometers. AMT, 17, 5029–5050, https://doi.org/10.5194/amt-17-5029-2024, 2024.

Daskalopoulou, V., et al.: Linear polarization signatures of atmospheric dust with the SolPol direct-sun polarimeter. AMT, 16, 4529–4550, https://doi.org/10.5194/amt-16-4529-2023, 2023.

García, R. D., et al.: Aerosol retrievals derived from a low-cost Calitoo sun-photometer taken on board a research vessel. Atmos. Environ., 341, 120888, https://doi.org/10.1016/j.atmosenv.2024.120888, 2025.

García, R. D., et al.: Impact of spectral aerosol radiative forcing at the Izaña observatory during the August 2023 extreme wildfires. AMT, 19, 3151–3167, https://doi.org/10.5194/amt-19-3151-2026, 2026.

Gidarakou, M., et al.: Exceptional wildfire smoke over Greece in summer 2023. ACP, 26, 4313–4339, https://doi.org/10.5194/acp-26-4313-2026, 2026.

González-Fernández, D., et al.: Retrieval of Solar Shortwave Irradiance from All-Sky Camera Images. Remote Sens., 16, 3821, https://doi.org/10.3390/rs16203821, 2024.

Graßl, S., et al.: From Polar Day to Polar Night: A Comprehensive Sun and Star Photometer Study of Trends in Arctic Aerosol Properties in Ny-Ålesund, Svalbard. Remote Sens., 16, 3725, https://doi.org/10.3390/rs16193725, 2024.

Gröbner, J., et al.: Spectral aerosol optical depth from SI-traceable spectral solar irradiance measurements. AMT, 16, 4667–4680, https://doi.org/10.5194/amt-16-4667-2023, 2023.

Guan, L., et al.: In-tandem multi-waveband particulate absorption and size observations yield substantial changes in radiative forcing over industrial Central China. Atmos. Chem. Phys., 26, 3107–3123, https://doi.org/10.5194/acp-26-3107-2026, 2026.

HARMONIA D3.2: Report on Aerosol Measurement Requirements for Different User Communities. Toanca, F., Solomos, S., Vandenbussche, S., Fountoulakis, I., Kazadzis, S. HARMONIA CA21119, 08 July 2025.

Herrero del Barrio, C., et al.: Analysis of Daytime and Night-Time Aerosol Optical Depth from Solar and Lunar Photometry in Valladolid (Spain). Remote Sensing, 15, 5362, https://doi.org/10.3390/rs15225362, 2023.

Herrero del Barrio, C., et al.: CAECENET: An automatic system processing photometer and ceilometer data from different networks to provide columnar and vertically-resolved aerosol properties. Plos One, 19 (12), e0311990, https://doi.org/10.1371/journal.pone.0311990, 2024.

Herrero del Barrio, C., et al.: Cloud height mapping using multi simultaneous sky images from an all-sky camera network, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2026-2694, 2026.

Herrero-Anta, S., et al.: Retrieval of aerosol properties from zenith sky radiance measurements. AMT, 16, 4423–4443, https://doi.org/10.5194/amt-16-4423-2023, 2023.

Herrero-Anta, S., et al.: Impact of cloud presence on sky radiances and the retrieval of aerosol properties, Atmos. Res., 317, 107938, https://doi.org/10.1016/j.atmosres.2025.107938, 2025.

Herrero-Anta, S., et al.: Exceptional high AOD over Svalbard in summer 2019: a multi-instrumental approach. ACP, 26, 1435–1457, https://doi.org/10.5194/acp-26-1435-2026, 2026.

Hou, X., et al.: Assessment of aerosol optical depth forecast for day-ahead clear-sky direct irradiance. AMT, 18, 4543–4557, https://doi.org/10.5194/amt-18-4543-2025, 2025.

Hrabčák, P., et al.: 30 years of total column ozone and aerosol optical depth measurements using the Brewer spectrophotometer in Poprad-Gánovce, Slovakia. ACP, 25, 16263–16286, https://doi.org/10.5194/acp-25-16263-2025, 2025.

Jaine, D., et al.: Total solar irradiance using a traceable solar spectroradiometer. AMT, 18, 7177–7186, https://doi.org/10.5194/amt-18-7177-2025, 2025.

Karanikolas, A., et al.: Intercomparison of AOD retrievals from GAW-PFR and SKYNET sun photometer networks and the effect of calibration. AMT, 17, 6085–6105, https://doi.org/10.5194/amt-17-6085-2024, 2024.

Karanikolas, A., et al.: Retrieval of aerosol properties from aerosol optical depth measurements with high temporal resolution and spectral range. AMT, 18, 7651–7677, https://doi.org/10.5194/amt-18-7651-2025, 2025.

Kouklaki, D., et al.: Photovoltaic Spectral Responsivity and Efficiency under Different Aerosol Conditions. Energies, 16, 6644, https://doi.org/10.3390/en16186644, 2023.

Kouklaki, D., et al.: The Effect of Atmospheric Variability in Measured Spectral Ultraviolet Radiation in Athens, Greece, During the ASPIRE Campaign. IOP Conf. Ser.: Earth Environ. Sci., 1522, 012037, https://doi.org/10.1088/1755-1315/1522/1/012037, 2025.

Kouklaki, D., et al.: Dust Radiative Effects and Impact on Energy Production over the Mediterranean Basin. EGUsphere [preprint], https://doi.org/10.5194/egusphere-2026-2775, 2026.

Li, Q., et al.: An ensemble machine learning method to retrieve aerosol parameters from ground-based Sun-sky photometer measurements. AMT, 19, 2507–2528, https://doi.org/10.5194/amt-19-2507-2026, 2026.

Masoom, A., et al.: Investigation of the effects of the Greek extreme wildfires of August 2021 on air quality and spectral solar irradiance. Atmos. Chem. Phys., 23, 8487–8514, https://doi.org/10.5194/acp-23-8487-2023, 2023.

Masoom, A., et al.: Assessment of the impact of NO2 contribution on aerosol-optical-depth measurements at several sites worldwide. AMT, 17, 5525–5549, https://doi.org/10.5194/amt-17-5525-2024, 2024.

Masoom, A., Kazadzis, S., Modini, R. L., Gysel-Beer, M., Gröbner, J., Coen, M. C., Navas-Guzman, F., Kouremeti, N., Brem, B. T., Nowak, N. K., Martucci, G., and Hervo, M.: Long range transport of Canadian wildfire smoke to Europe in 2023: aerosol properties and spectral features of smoke particles, Atmos. Chem. Phys., 26, 10801–10834, https://doi.org/10.5194/acp-26-10801-2026, 2026.

Mateos, D., et al.: Saharan and Arabian dust optical properties registered by sun photometry during A-LIFE field experiment in Cyprus. ACP, 26, 1993–2005, https://doi.org/10.5194/acp-26-1993-2026, 2026.

Moustaka, A., et al.: Assessing Lidar Ratio Impact on CALIPSO Retrievals for Aerosol SW Radiative Effects across North Africa, Middle East and Europe. Remote Sens., 16, 1689, https://doi.org/10.3390/rs16101689, 2024.

Moustaka, A., et al.: Enhancing dust aerosols monitoring capabilities across North Africa and the Middle East using the A-Train satellite constellation. AMT, 19, 1201–1225, https://doi.org/10.5194/amt-19-1201-2026, 2026.

Nicolae, D., et al.: Examining the characteristics of aerosols: a statistical analysis based on a decade of lidar and photometer observations at the Eastern border of

ACTRIS. Atmos. Meas. Tech., 19, 1179–1199, https://doi.org/10.5194/amt-19-1179-2026, 2026.

Papachristopoulou, K., et al.: Effects of clouds and aerosols on downwelling surface solar irradiance nowcasting and short-term forecasting. AMT, 17, 1851–1877, https://doi.org/10.5194/amt-17-1851-2024, 2024.

Papadimitriou, N., et al.: PV power modelling using solar radiation from ground-based measurements and CAMS. AMT, 19, 1227–1244, https://doi.org/10.5194/amt-19-1227-2026, 2026.

Proestakis, E., et al.: Atmospheric dust and air quality over large-cities and megacities of the world. Atmos. Chem. Phys., 25, 14777–14823, https://doi.org/10.5194/acp-25-14777-2025, 2025.

Pulimeno, S., et al.: Recent advances in aerosol optical depth measurements in polar regions: insights from the Polar-AOD Program. ACP, 26, 1809–1846, https://doi.org/10.5194/acp-26-1809-2026, 2026.

Román, R., et al.: Star photometry with all-sky cameras to retrieve aerosol optical depth at nighttime. AMT, 18, 2847–2875, https://doi.org/10.5194/amt-18-2847-2025, 2025.

Sánchez-Barrero, M. F., et al.: Aerosol variability over oceans using micro-pulse lidar and photometer: insights from TRANSAMA ship-based campaign. AMT, 19, 507–528, https://doi.org/10.5194/amt-19-507-2026, 2026.

Solomos, S., et al.: The Development of METAL-WRF Regional Model for the Description of Dust Mineralogy in the Atmosphere. Atmosphere, 14, 1615, https://doi.org/10.3390/atmos14111615, 2023.

Spyrou, C., et al.: Implications of dust minerals on radiative transfer at regional scale, using the METAL-WRF model. AMT, 18, 7717–7734, https://doi.org/10.5194/amt-18-7717-2025, 2025.

Torres, B., et al.: Adaptation of the CIMEL-318T to shipborne use: 3 years of automated AERONET-compatible aerosol measurements on board the research vessel Marion Dufresne. AMT, 18, 4809–4838, https://doi.org/10.5194/amt-18-4809-2025, 2025.

Tsekeri, A., et al.: Combined sun-photometer–lidar inversion: lessons learned during the EARLINET/ACTRIS COVID-19 campaign. Atmos. Meas. Tech., 16, 6025–6050, https://doi.org/10.5194/amt-16-6025-2023, 2023.

Zhu, J., et al.: The radiative forcing of PM2.5 heavy pollution, its influencing factors and importance to precipitation during 2014–2023 in the Bohai Rim, China. ACP, 26, 5679–5696, https://doi.org/10.5194/acp-26-5679-2026, 2026.

This report was produced under the COST Action CA21119 HARMONIA "International network for harmonization of atmospheric aerosol retrievals from ground based photometers", supported by COST (European Cooperation in Science and Technology).