Milestone 4: Documentation of calibration, standard operation and processing

Authors: Honey Alas, Alfred Wiedensohler, Doina Nicolae, Betsy Andrews, Anca Nemuc, Kay Weinhold, Olga Mayol-Bracero and Janek Uin

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1. Introduction

This report documents the calibration, standard operation and processing protocols (collectively referred to as "protocols") for the 8 target atmospheric variables of CARGO-ACT to serve as the project milestone (M4) from WP2. The main documentation is a spreadsheet - linked here - of the existing protocols and standards from different entities within the EU, US, and globally. This documentation will serve as the foundation of CARGO-ACT's harmonising and capacity building activities, and from which deliverable D2.1 will be developed. The documentation is extensive but will be a living document as we continue to consult relevant stakeholders throughout the project.

As a starting point, we begin the report with an introduction of the protocols for each category at global scale. The Scientific Advisory Group (SAG) for Aerosols published the "WMO/GAW Aerosol Measurement Procedures, Guidelines and Recommendations" (GAW report 227) for aerosol measurements within the WMO-GAW program. This GAW report is the second edition (published in 2016), following GAW report 153.

GAW report 227 covers variables for aerosol in-situ (IS) and remote sensing (RS) measurements and data reporting. The chapters for aerosol IS describe a) sampling & conditioning, b) chemical analysis, c) optical variables, d) microphysical variables, and e) cloud condensation nuclei. The chapters for RS describe techniques, methods, and variables for aerosol optical depth and lidar measurements. The last chapter in the report refers to the data reporting to the World Data Center for Aerosol (WDCA), covering the data submission for regular data, advanced (traceable) regular data, and Near-Real-Time data.

Members of the SAG included aerosol experts from different fields (such as modeling, aerosol IS, aerosol RS) as well the representatives of the GAW calibration centres, data centre, and networks (infrastructures). The content of GAW report 227 was influenced and written by representatives from NOAA and ACTRIS (involved in IS, RS, and data reporting).

From here, these protocols have been further developed over time within the Aerosol, Clouds, and Trace Gases Research Infrastructure (ACTRIS). In 2023, the European Commission approved the establishment of ACTRIS as a European Research Infrastructure Consortium (ACTRIS-ERIC). Shortly after, ACTRIS published the latest version of the ACTRIS standards which are more detailed than those in the GAW report, and with updated protocols for both IS and RS variables. These standards are used within the EU and other partner observatories across the globe.

For each category in this report, the ACTRIS Standards are itemised, serving as the basis for comparison with other protocols (global, US, etc.). From here, common items are identified, as are any major differences between the different protocols.

The report proceeds as follows; the atmospheric variables are grouped into two branches with protocols relevant to in-situ (IS) described in Chapter 2 and protocols relevant to remote sensing (RS) variables described in Chapter 3.

The protocols collected are partitioned into three main categories:

A. General protocols - standards which are not specific to any variable but mainly for general aerosol measurements;
B. Protocols for traceability and calibration facilities - standards pertaining to the setup and operation of a calibration facility for the specific atmospheric variables;
C. Standard operating procedures (SOP) at the station/observatory - standards pertaining to the measurement of each variable which are applied or used by large measurement networks.

The detailed documentation of the protocols can be found here:

CARGO-ACT: Documentation of Protocols

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2. Protocols for IS variables

The following protocols are specific to the 4 atmospheric variables listed in Table 1. The table also includes the measurement methods/instrumentation widely used with existing standardized protocols.

Table 1: List of IS variables and relevant measurement principle/instrument.

IS Variables	measurement methods/instrumentation
particle number size distribution (10-800nm)	mobility particle size spectrometers (MPSS)
particle number concentration Dp50 = 10nm	condensation particle counters (CPC)
particle light absorption coefficient	absorption photometer (AP)
particle light scattering coefficient	integrating nephelometer (IN)

2.1 GAW report 227 for IS variables (Global)

Chapters 4 and 5 in GAW report 227 cover the microphysical and optical IS variables for CARGO-ACT as listed in Table 1 and were thus used as the basis for the current ACTRIS Standard Procedures for In-Situ Aerosol Sampling, Measurements, and Analyses at ACTRIS Observatories. At the time of its publishing (2016), the recommendations outlined in this report were general and more focused on SOPs at observatories (or measurement stations). A chapter on general archiving procedures (Chapter 9) is also included in this report. Protocols for the calibration of instruments are largely based on scientific publications, instrument manuals, and few standardization documents (i.e. International Organization for Standardization, ISO; European Commission for Standardization, CEN). Several of these recommendations are still in use and are part of the new protocols.

2.2 ACTRIS protocols (EU)

In January of 2024, ACTRIS-ERIC released the first version of the ACTRIS Standard Procedures for In-Situ Aerosol Sampling, Measurements, and Analyses at ACTRIS Observatories led by the Centre for Aerosol In Situ - European Centre for Aerosol Calibration (CAIS-ECAC). As mentioned above, the ACTRIS standard procedures were developed from WMO/GAW Reports 227 (2016) and 200 (2011) and have been significantly expanded and improved upon in the years that followed with standardised documents, project reports, and the expertise held within CAIS-ECAC.

2.2.1 General protocols

The general recommendations covering aerosol sampling & conditioning and data processing largely remain the same as in WMO/GAW Report 227. The main change is the requirement that the aerosol in situ online instrumentation (applicable to the IS variables in CARGO-ACT which are also the core atmospheric variables in ACTRIS) is compatible with ACTRIS-Near-Real-Time (NRT) data software.

2.2.2 Protocols for traceability and calibration facilities

Prior to ACTRIS-ERIC, the World Calibration Centre for Aerosol Physics (WCCAP) under ECAC served as the main calibration centre for in situ instruments measuring the ACTRIS core variables. Established in 2002,

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WCCAP has been developing the calibration facility and procedures which contributed to several standardization documents and guidelines. It was only recently that the WCCAP begun creating the protocols for establishing a calibration facility for the four IS variables in lieu of the ACTRIS expansion including the new Prague Aerosol Calibration Centre (PACC). Within the ACTRIS-ERIC Standard Procedures, WCCAP and PACC follow standardised guidelines and technical specifications for the traceability and calibration of the instruments for measuring two of the IS variables:

- particle number size distribution (10-800nm) – MPSS
  - CEN/TS 17434:2020 - Ambient air - Determination of the particle size spectra of atmospheric aerosol using a mobility particle size spectrometer (MPSS)
  - ISO 15900:2020 - Determination of particle size distribution — Differential electrical mobility analysis for aerosol particles
- particle number concentration Dp50 = 10nm (CPC)
  - ISO 27891:2015 - Aerosol particle number concentration - Calibration of condensation particle counters
  - EN 16976:2024 (formerly CEN/TS 16976:2016) - Ambient Air - Determination of the particle number concentration of atmospheric aerosol

These are also summarised in the "Performance & evaluation criteria for calibration workshops & ACTRIS compatibility", documented for each IS variable, and can be found on the CAIS-ECAC website.

For particle light absorption and scattering coefficients there are no recent standardised guidelines such as CEN or ISO standards; standards for these variables are mainly based on scientific publications (Petzold et al., 2004, 2013; Hitzenberg et al., 2006; Müller et al., 2011) and instrument manuals.

2.2.3 SOP at the station/observatory

Alongside the general recommendations (2.2.1), ACTRIS also provides measurement guidelines for these IS variables. These SOPs are based on the protocols and standardized guidelines and technical specifications mentioned above. More explicitly, the existing ACTRIS Recommendations for the IS variables are described in the following documents:

- particle number size distribution (10-800nm) – MPSS
  - ACTRIS Recommendation for MPSS measurements: Part I recommended instrument set-up
  - ACTRIS Recommendation for MPSS measurements: Part II recommended particle loss correction
  - ACTRIS Recommendation for MPSS measurements: Part III Standard Operation Procedure
  - ACTRIS Recommendation for MPSS measurements: Part IV Constants and Relevant Equations
  - ACTRIS In Situ Aerosol: Guidelines for Manual QC of MPSS Data
- particle number concentration Dp50 = 10nm - CPC

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    - covered by the EN 16976:2024 and WMO/GAW Report No. 227
- particle light absorption coefficient – AP
    - ACTRIS In Situ Aerosol: Guidelines for Manual QC of AE33 absorption photometer data
    - ACTRIS In Situ Aerosol: Guidelines for Manual QC of MAAP (Multiangle Absorption Photometer) data
- particle light scattering coefficient – IN
    - ACTRIS Recommendations for Ecotech Integrating Nephelometers: Part 1 Recommended instrument setup
    - ACTRIS Recommendations for Ecotech Integrating Nephelometers: Part 2 Standard operating procedure
    - ACTRIS In Situ Aerosol: Guidelines for Manual QC of TSI 3563 Integrating Nephelometer Data
    - ACTRIS In Situ Aerosol: Guidelines for Manual QC of Ecotech Aurora 4000/3000 Integrating Nephelometer Data

The ACTRIS Standards are followed by all ACTRIS stations (75 across Europe and at selected global sites) as well as in many WMO/GAW stations. In Germany, ambient air monitoring stations operated by the local and national agencies such as the German Environment Agency (UBA), German Weather Service (DWD), German Ultrafine Aerosol Network (GUAN), and stations at the state level also follow the ACTRIS standards for these IS variables. In the US, the newly established Atmospheric Science and Chemistry Measurement Network (ASCENT) follows largely the ACTRIS standards for measurement by MPSS and AP. Since the ACTRIS protocols are based on WMO/GAW reports 227 and 200, which are also the basis for the protocols in the US and other countries, there are several aspects which are already harmonised.

2.3 NOAA Federated Aerosol Network - NFAN (US)

2.3.1 General protocols

Similar to ACTRIS, the general recommendations for aerosol sampling & conditioning and data processing largely remain the same as in WMO/GAW Report 227. The primary difference is that some NFAN sites (Andrews et al., 2019) utilise gentle heating to lower the sample RH. Many of these sites have limited budget or personnel to implement more sophisticated drying techniques and some studies at NFAN sites have suggested minimal impact by heating (e.g., Bergin et al., 1997). Additionally, sites have no active heating but heating occurs because the building in which the instrument is installed is significantly warmer than the outside environment (e.g., in polar environments). A limitation of gentle heating is that is not always sufficient to lower sample RH for some environments/seasons).

The typical basic instrument suite at an NFAN site are a nephelometer (to measure aerosol scattering), a filter-based absorption photometer (to measure aerosol absorption) and a condensation particle counter (to measure aerosol number concentration). NFAN recognises that different partners have different scientific interests as well as different instrumentation that they may want to include in their measurement suite. NFAN does not require specific instrumentation or variables, rather it tries to support partner interests to the extent possible. This is done through software which has the capability of providing data acquisition, data review, data QC and NRT data submission to EBAS in one integrated end-to-end software package. A list of instruments that have previously been supported by the NOAA software is provided on the NOAA website, although a newer version of the software no longer includes some of these instruments as they are no longer being used at any of the NFAN sites.

2.3.2 Protocols for traceability and calibration facilities

NOAA does not operate a calibration facility for the basic instrument suite (nephelometer, AP, CPC). NOAA generally prefers to keep instruments in the field and monitor their housekeeping parameters (flow rates, measurement conditions, instrument specific parameters) until there is a problem. This minimizes downtime and potential instrument damage or loss due to shipping. The incoming data is inspected on a daily basis and, at the very least, data QC is performed on all instruments on a weekly basis in order to identify instrument issues quickly. NOAA recommends that their partners do the same. NFAN documentation for the data review and QC includes information on how to identify many common problems (e.g., failed pumps and broken valves and dying lamps in the nephelometer). The following checks are performed to provide confidence in the measurements.

The nephelometer is easily calibrated with CO_2 and filtered air and is done prior to shipping to a site, on arrival at a site and then checks of the calibration (so-called 'span checks') are performed monthly at the site. Automated hourly zeroes (so-called 'background checks') are also performed while the nephelometer is deployed in order to track issues that might arise due to instrument contamination or leaks. Span check and background values are recorded as parameters in the software and are easily retrieved.

Additionally, NOAA has developed expertise and documentation on identifying problems with nephelometers based on the data that comes in from the stations hourly and provides documentation describing standard maintenance and less standard repairs for the nephelometer (specifically the TSI 3563 integrating nephelometer) on their website. NOAA experts were also the primary authors of the WMO/GAW nephelometer operations guide (Chapter 6 in GAW report 200).

There is currently no accepted calibration technique for filter-based absorption instruments so these instrument checks are made at the observatory and include flow and leak checks. For the Continuous Light Absorption Photometer (Ogren et al., 2017) parameters such as light source intensity and flow are tracked and provided in the hourly data sent back from the station. Intercomparisons can be made when there are multiple APs at the same site. For the AE33 Aethalometer the manufacturer recommended tests are performed during annual maintenance visits (flow check/calibration, clean air tests, etc.)

For CPCs, 30-40-year-old TSI 3760 butanol-based counters are operated at most of the sites. Prior to sending an instrument to a site and after repairs (e.g., laser replacement or butanol block cleaning) the instrument is operated side-by-side with a laboratory standard TSI 3010 calibrated at the WCCAP and only used to evaluate other particle counters. If the comparisons with the lab standard are within 5% then it is assumed that the tested instrument is ready for deployment. The network is currently transitioning to new water-based counters and protocols are being developed for them. Currently, there are both butanol-based and water-based counters running side by side at 6 sites; the intercomparisons give confidence in both the old particle counters and the new instruments.

2.3.3 SOP at the station/observatory

Some of what is described above should probably be within SOP rather than calibration, but that is because there is no calibration facility. A SOP for the aerosol suite is provided to station technicians and partners and includes using daily check sheets to make sure all the instruments and peripherals are operating within specifications together with daily, weekly and monthly maintenance checks. Additionally, there is documentation describing the annual maintenance procedures which are performed by a NOAA scientist during yearly visits to the sites. All calibrations and checks made during annual maintenance are kept in station specific directories at NOAA for easy reference.

2.4 Atmospheric Radiation Measurement – ARM (US)

2.4.1 Background and general protocols

In 1990, the U.S. Department of Energy (DOE) started ARM to reduce the uncertainty in climate models for the purpose of improving climate change predictions by collecting observations over a range of atmospheric conditions in climatically important regions of the world (Turner and Ellingson, 2016). The objective of these observations is progress science. The US congress funds DOE to run ARM as a national user facility.

ARM in-situ aerosol measurements made with the Aerosol Observing System (AOS) are particle number concentration, hygroscopicity, optical properties, chemical composition, and trace gases (Uin et al., 2019; Theisen et al., 2024).

A standard AOS includes the following instruments: aerodynamic particle sizer (APS), cloud condensation nuclei counter (CCNC), condensation particle counter (CPC/CPCf), impactor, nephelometer, ozone (O_3) monitor, particle soot absorption photometer (PSAP), scanning mobility particle sizer (SMPS), ultra-high-sensitivity aerosol spectrometer (UHSAS) and AOS meteorological system (AOSMET). Additional instruments may be deployed full-time at certain sites or during intensive operation periods (IOPs). These are: aerosol chemical speciation monitor (ACSM/ACSM-TOF), aethalometer, carbon monoxide monitor, ultrafine CPC, cavity attenuated phase shift monitor (CAPS), filter for ice nucleation particles, humidified tandem differential mobility analyser (HT-DMA), nano SMPS, sulfur dioxide monitor, single particle soot photometer (SP2).

There are three fixed locations and three mobile facilities distributed across diverse climate regimes. The first location established was SGP (Southern Great Plains) in Oklahoma, where AOS measurements started in 1996. The other fixed location where in-situ aerosol measurements are performed is known as ENA (Eastern North Atlantic) in the Azores and measurements started in 2013. ARM has a 3rd fixed location in the North Slope of Alaska (NSA) and in-situ aerosol measurements of coarse mode aerosol (APS) and aerosol chemical composition (ACSM and SP2-XR) will start in September 2024. The mobile facility

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deployments run from six months to two years and extend the ability for ARM to sample a wide range of environments.

The AOS deployments are managed by the AMF operator, instruments are operated under the direction of the mentors, and on-site operators fill in daily checklist during campaigns. The data are collected by LabView programs, these programs write data to a file where ARM "ingest" routines collect them, data is written to NetCDF files, QA/QC checks and calibrations are made, and data then become available to the public in near-real time through the centralized ARM Data Center. All primary data are consistently saved at the highest instrument time resolution.

ARM has developed its own (mentor) protocols based on literature, best practices identified by the wider community, and mentor expertise. Constraints due to availability of resources and site access have also been considered. The protocols are published on the ARM website in Instrument Handbooks (https://www.arm.gov/capabilities/instruments/aos).

2.4.2 Protocols for traceability and calibration facilities

ARM instruments are calibrated following schedules developed for each instrument by the respective instrument mentor. The calibration schedules are based on specific instrument needs with constraints such as access to the instrument and availability of calibration equipment taken into account. ARM is in the process of formalising the schedules to increase the transparency of the calibration processes and to better align calibrations with other activities such as during IOPs.

ARM does not currently operate a calibration facility for in-situ aerosol measurements. This is, however, changing with ARM investing in equipment and infrastructure for the establishment of a gold-standard reference for size distribution (SMPS) and number concentration measurements (CPC). This equipment will be deployed at the Center for Aerosol Measurement Science (CAMS) at Brookhaven National Laboratory (BNL). The standards will then be compared with World Calibration Center for Aerosol Physics (WCCAP) standards every other year. This effort is part of CARGO-ACT.

2.4.3 SOP at station/observatory

ARM provides measurement guidelines for aerosol IS variables through their instrument handbooks. Links to the handbooks are listed here.

- Particle number size distribution – SMPS
  - Scanning Mobility Particle Sizer (SMPS) Instrument Handbook. DOI: 10.2172/1245993
- Particle number concentration Dp50 = 10 nm - CPC
  - Condensation Particle Counter (CPC) Instrument Handbook. DOI: 10.2172/1245983
- Particle light absorption coefficient – AP
  - Aethalometer Instrument Handbook. DOI: 10.2172/1251391
  - Particle Soot Absorption Photometer (PSAP) Instrument Handbook. DOI: 10.2172/1246162
- Particle light scattering coefficient – IN
  - Nephelometer Instrument Handbook. DOI: 10.2172/1246075

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3. Protocols for RS variables

Table 2: List of RS variables and relevant measurement principle/instrument.

IS Variables	measurement methods/instrumentation
particle backscatter coefficient profile	aerosol high-power lidar (elastic / multi-wavelength / high-spectral resolution)
particle extinction coefficient profile	aerosol high-power lidar (Raman / multi-wavelength / high spectral resolution)
particle depolarization ratio profile	aerosol high-power lidar (polarization)
particle layer geometrical properties	aerosol high and low-power lidar, ceilometer

3.1 WMO/GAW report 227 for RS variables (Global)

The GAW report 227 (Table 8.1, page 71) covers the geometrical and optical aerosol RS variables for CARGO-ACT listed in Table 2. Please note that: a) column aerosol measurements are already globally standardized through AERONET and, therefore, are not within the remit of CARGO-ACT; b) additional variables can be obtained from multi-wavelength lidar and/or by synergy with collocated sun/sky/lunar photometers: aerosol lidar ratios, Angstrom exponent, colour ratios, fine and coarse mode volume concentrations, etc. However, these are subject to the availability of particular lidar channels and/or collocated photometer, and therefore out of the primary scope of CARGO-ACT.

The GAW report 227 inherited from AERONET, EARLINET, NDACC, E-PROFILE and MPL developments which are also the basis for the current ACTRIS Standard Procedures for Aerosol Remote Sensing at ACTRIS Observatories. The GAW Aerosol LIdar Observation Network (GALION) has, and is playing a crucial role in connecting continental aerosol lidar networks, and advocating for the harmonisation of lidar data products. The standards in use for quality assurance of the measurements, as well as the data processing algorithms, are still not harmonised at global scale, except for NDACC lidars (NDACC being already a global network, however with few observation sites).

3.2 ACTRIS protocols (EU)

3.2.1 General protocols

Although ACTRIS-ERIC was formally established in April 2023, several protocols were issued beforehand to allow the operations of the existing aerosol remote sensing observatories (candidate ACTRIS National Facilities). Statements in these documents describe:

a) the decisions of the Interim ACTRIS Council referring to the general requirements for an ACTRIS aerosol remote sensing National Facility, as described in “D5.1 Documentation on technical concepts and requirements for ACTRIS observational platforms“;
b) specific operation procedures and quality assurance for the aerosol high-power lidars (capitalizing on the previous work in EARLINET and up-scaled to ACTRIS requirements);

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c) the EARLINET Single Calculus Chain (SCC) for centralized processing of raw lidar data;
d) specific operation procedures and quality assurance for automatic sun/sky/lunar photometer in use at AERONET.

All protocols are in line with the global protocols currently available and described in GAW report 227, however they are more detailed. One important detail is the mandatory use of the SCC for processing the raw lidar data, with an operational configuration that is annually validated against specific quality assurance check-ups applied to the instruments.

3.2.2 Protocols for traceability and calibration facilities

The ACTRIS calibration facility responsible for aerosol RS is the Centre for Aerosol Remote Sensing (CARS). CARS emerged from the union of the AERONET-EU calibration facilities for automatic sun/sky/lunar photometers (ASP), and the EARLINET calibration facilities for the aerosol high-power lidars (AHL). Due to the similar design and data treatment, calibration of ceilometers was entrusted also to CARS, although in ACTRIS these instruments are currently used as part of cloud remote sensing facilities. CARS is responsible for the quality assurance of the lidar, photometer and ceilometer measurements. CARS is closely linked to the Aerosol Remote Sensing Data Centre Unit (ARES), which operates the SCC. ARES is responsible for the processing and quality assurance of the lidar and photometer data products.

CARS and ARES have issued a comprehensive document which describes the requirements for the instruments and for the data processing of aerosol RS measurements: **Guidelines and recommendations for the candidate ACTRIS Aerosol Remote Sensing Observational Platforms**

Version 01 of this document was issued in November 2021 and published on the ACTRIS website. This document describes the requirements in terms of instruments and data processing for aerosol high-power lidars and for the automatic sun/sky/lunar photometers. The main requirements are:

a. collocation of an aerosol high-power lidar and an automatic sun/sky/lunar photometer (less than 1 km horizontal distance);
b. at least one elastic, one Raman and one polarization channel at the same wavelength for the lidar (with specific requirements for each channel);
c. mandatory use of the SCC for processing of raw lidar measurements;
d. at least 5 lidar observations per week, each with a duration of minimum 3 hours, following specified time intervals (2 during daytime and 3 during night-time);
e. standard Cimel photometer not older than 15 years;
f. continuous operation of the photometer at least during daytime (preferably also lunar measurements during night-time).

Version 02 of this document was issued and published in October 2022. The description of the operation of high spectral resolution lidar was removed because of the lack of capacity to offer support for QA/QC and data processing. This opens up the potential for the transfer of expertise from US to Europe. For details please refer to the document.

3.2.3 SOP at the station/observatory

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CARS and ARES have also issued and published operation and quality assurance procedures for aerosol high-power lidars:

High Power Lidar: Standard Operation Procedures for NF operation.

Version 01 of the document was issued in November 2023. The document describes the general operation procedures to be considered for all AHLs operated at ACTRIS aerosol remote sensing observatories:

- **Installation**: preparation of the AHL environment (instrument location, environmental temperature and humidity considerations, outgoing window, connection with a power supply, diffuse reflections, Interference with and from nearby instruments); preliminary set up of the instrument; on-site installation tests, preparation of the operation and maintenance logbook
- **Operation**: check-up of the AHL environment; check-up of the lidar; switching on the lidar (laser; polarization calibrator; electronics; checking the alignment); performing the measurements (dark measurement; normal measurement; polarization measurement); finalizing the measurements (submission of the raw data; filling in the operation logbook)
- **Maintenance**: laser; emission optics; receiving optics; filling in the maintenance logbook

High Power Lidar: Standard Quality Assurance Procedures for NF operation.

Version 01 of the document was issued in January 2024. The document describes the general instrument quality assurance procedures to be considered for all AHLs operated at ACTRIS aerosol remote sensing observatories:

- **Telecover test**: about the test; environmental conditions; test procedure (biaxial systems; coaxial systems); schedule; internal analysis (with example); filling in the QA logbook
- **Polarization calibration**: about the test; environmental conditions; test procedure; schedule; Internal analysis (with example); filling in the maintenance logbook
- **Rayleigh fit test**: about the test; environmental conditions; test procedure; schedule; internal analysis (with example); filling in the maintenance logbook
- **Zero bin test**: about the test; environmental conditions; test procedure (elastic channels; inelastic channels); schedule; internal analysis (with example); filling in the maintenance logbook
- **Extended Dark signal measurement**: about the test; environmental conditions; test procedure; schedule; internal analysis; filling in the maintenance logbook

The protocols listed above are followed by all ACTRIS aerosol remote sensing National Facilities and associated EARLINET stations (currently 33 fixed and 6 mobile facilities; up to 43 fixed and 7 mobile facilities by 2027).

Although desirable, it is not foreseen for the near future that these protocols (or similar) could be taken up by GALION. Lidars and lidar networks are still too diverse, so the operation and the quality assurance procedures must be adjusted to the design and limitations of each. Moreover, there are few lidar networks in the world that could coordinate the implementation of these procedures at significant scale. In most

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cases, lidar calibration is performed either by direct comparison with a reference instrument, or by checking the data products.

The experience in Europe is that side-by-side comparison of instruments does not provide reliable calibration of aerosol high-power lidars. Calibration is lost as soon as the instrument is moved or the operator changes the settings. Also, the instrument performances may change with time. The operator should be skilled and have in-depth knowledge about the instrument in order to keep it well-calibrated. On the other hand, quality checks applied to the data products do not completely remove instrumental problems and generally it does not guarantee realistic estimation of the uncertainties. The processing algorithms and the atmospheric variability usually hinder instrumental biases, leading to an underestimation of the uncertainties.

Therefore, the strategy at CARS is to characterise the instruments at hardware level, and to apply regular tests for checking the stability. The scope of the quality assurance tests described in CARS protocols is twofold:

a) to quantify instrumental biases and calculate correction factors that are further used in the data processing (e.g. altitude of full overlap, maximum altitude range, calibration factor for the polarization channels, trigger delay and zero bin for correct gluing of the analogue and photon counting channels);
b) to identify potential instrumental problems and make optimizations (e.g. misalignment, instability of the electronic noise, improper optical chain, inhomogeneity of the photodetectors, etc.).

The tests are performed regularly by the operators in order to keep the instrument operating at nominal performance. Once per year test data is analysed by CARS, which may recommend optimizations and/or adjustment of the SCC operational configuration to match the status of the instrument.

The quality assurance tests are time and resource demanding, however they are generally applicable to multi-wavelength Raman polarization lidars, and they give a thorough understanding of the lidar limitations and measurement uncertainty.

While working for more standardized instruments which could simplify the operation and the quality assurance procedures, there are several aspects that could be addressed for harmonising the quality of the lidar data products globally, such as:

a. development of generally applicable standard tests and tools for identification of systematic biases and correction factors;
b. continuous training of the operators to enable quality control of the measurements;
c. adoption of common signal correction and data processing algorithms.

Automatic low-power lidars and ceilometers (ALC) are standardised instruments for which simple protocols can be applied. Protocols have been developed for the EUMETNET E-PROFILE ceilometer network and are now under extension at CARS to enable quality assurance of the instruments operating at the ACTRIS cloud remote sensing observatories (currently 15 fixed and 5 mobile; up to 23 fixed and 6 mobile facilities by 2027). ALC data is used in ACTRIS to distinguish between aerosols and clouds, and to retrieve the aerosol layer geometrical features, but no quantitative aerosol products are extracted. With one wavelength, a limited dynamic altitude range, and a quite low signal-to-noise ratio (especially during daytime), the calibration of ALC data for retrieving aerosol backscatter profiles is considered not yet possible. A MoU between ACTRIS and E-PROFILE is under discussion to enable long-term collaboration, e.g. the use of the same quality assurance procedures in ACTRIS and E-PROFILE (more than 440 ceilometers in Europe).

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