Milestone 4: Documentation of calibration, standard operation and processing

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Contents

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 andstandards from different entities within the EU, US, and globally. This documentation will serve as thefoundation 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 consultrelevant stakeholders throughout the project.

As a starting point, we begin the report with an introduction of the protocols for each category at globalscale. 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, aerosolRS) 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 fromNOAA 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 establishmentof 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 EUand other partner observatories across the globe.

For each category in this report, the ACTRIS Standards are itemised, serving as the basis for comparisonwith 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:

1. **General protocols** - standards which are not specific to any variable but mainly for general aerosol measurements;
2. **Protocols for traceability and calibration facilities** - standards pertaining to the setup and operation of a calibration facility for the specific atmospheric variables;
3. **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

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 aslisted in Table 1 and were thus used as the basis for the current ACTRIS Standard Procedures for In-SituAerosol 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 alsoincluded 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 recommendationsare 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 InSitu - 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 insitu 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 themain calibration centre for in situ instruments measuring the ACTRIS core variables. Established in 2002, 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 suchas CEN or ISO standards; standards for these variables are mainly based on scientific publications (Petzoldet 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 theseIS 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
    - 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 localand 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 ChemistryMeasurement 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 theprotocols 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 siteshave suggested minimal impact by heating (e.g., Bergin et al., 1997). Additionally, sites have no activeheating 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 notalways 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), afilter-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 includessome 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, onarrival at a site and then checks of the calibration (so-called ‘span checks’) are performed monthly at thesite. 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 aretracked and provided in the hourly data sent back from the station. Intercomparisons can be made whenthere are multiple APs at the same site. For the AE33 Aethalometer the manufacturer recommended testsare 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 isassumed that the tested instrument is ready for deployment. The network is currently transitioning tonew 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 andpartners 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 modelsfor 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 nationaluser 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. Thefirst location established was SGP (Southern Great Plains) in Oklahoma, where AOS measurements startedin 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 inthe 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 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 directionof the mentors, and on-site operators fill in daily checklist during campaigns. The data are collected byLabView programs, these programs write data to a file where ARM "ingest" routines collect them, data iswritten to NetCDF files, QA/QC checks and calibrations are made, and data then become available to thepublic in near-real time through the centralized ARM Data Center. All primary data are consistently savedat 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 alsobeen 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 constraintssuch as access to the instrument and availability of calibration equipment taken into account. ARM is inthe process of formalising the schedules to increase the transparency of the calibration processes and tobetter 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 equipmentwill 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. Linksto 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 RS variables

CARGO-ACT focuses on four aerosol remote sensing variables. which can be measured by various lidar techniques.

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

RS Variables	Measurement methods/instrumentation
Aerosol particle backscatter coefficient profile	CL, BL, BL_SP, RL, HSRL, MWBL, MWBL_SP, MWRL, MWHSRL
Aerosol particle light extinction coefficient profile	RL, HSRL, MWRL, MWHSRL, BL_SP (estimated)
Aerosol particle depolarization ratio profile	L_PL, CL_SP_PL, BL_PL, BL_SP_PL, RL_PL, HSRL_PL, MWBL_PL, MWBL_SP_PL, MWRL_PL, MWHSRL_PL
Aerosol layer geometrical properties: ● Aerosol layer base altitude ● Aerosol layer top altitude	CL, BL, RL, HSRL, MWBL, MWRL, MWHSRL, DWL, DIAL, IPDIAL

Definition of variables is taken from ACTRIS Vocabulary. Lidar types and codes are taken from GALION Data and Instrumentation, where mapping to the WIGOS metadata standards is provided. WMO Integrated Global Observing System (WIGOS) provides a collective identity for all WMO observing systems, and a framework for enabling their integration, interoperability, optimized evolution and best-practice operation. Lidar types which are considered in CARGO-ACT for potential harmonization are marked in bold.

Table 3: List of instrument codes

Code	Instrument	WIGOS	WIGOS_name
CL	Ceilometer	245	Ceilometer
BL	Backscatter Lidar	341	Backscatter lidar
RL	Raman Lidar	143	Raman lidar
HSRL	High Spectral Resolution Lidar	342	High spectral resolution (HSR) lidar
DWL	Doppler Wind Lidar	142	Doppler wind lidar
DIAL	Differential Absorption Lidar	335	Differential absorption lidar (DIAL)
IPDIAL	Integrated Path Differential	320	Integrated path differential

	Absorption Lidar		absorption (IPDA) lidar
PL	Polarized Lidar	pending	pending
MWBL	Multi-Wavelength Backscatter Lidar	341	Backscatter lidar
MWRL	Multi-Wavelength Raman Lidar	143	Raman lidar
MWHSRL	Multi-Wavelength High Spectral Resolution Lidar	342	High spectral resolution (HSR) lidar
MWPL	Multi-Wavelength Polarized Lidar	pending	pending

3.1 Global protocols

The GAW report 227 (Table 8.1, page 71) covers the geometrical and optical aerosol RS variables for CARGO-ACT as listed in Table 2. The GAW report 227 was inherited from the GAW Report No. 178: GALION Implementation Plan (2008). GALION (GAW Aerosol LIdar Observation Network) is a network of lidar networks organized through the GAW program to coordinate activities and provide comprehensive global profiling of atmospheric aerosols and clouds. EARLINET, NDACC, and MPLNET are GALION networks. GALION chair and steering committee leadership is run by the heads of the individual lidar networks. Each GALION network is an official GAW contributing network (signed letter of agreement with WMO). GALION plays a crucial role in connecting regional and global aerosol lidar networks, and advocating for harmonization of 1) lidar data products, 2) observation methods, 3) calibration and QC/QA, and 4) processing techniques. Progress has been made on topics 1-2 and GALION vocabularies and instrument methodology forms the basis for CARGO-ACT. However, GALION harmonization of topics 3-4 across all networks is in progress. CARGO-ACT will establish a framework to achieve these goals between ACTRIS, MPLNET, and ARM, and thereby support GALION objectives as well.

MPLNET (NASA Micro-Pulse Lidar Network) is a global federated network of Micro-Pulse Lidar (MPL) systems designed to measure aerosol and cloud vertical structure, and boundary layer heights. Most MPLNET sites are co-located with sites in the NASA Aerosol Robotic Network (AERONET). EARLINET and the European NDACC aerosol lidars are currently part of ACTRIS (the Aerosol, Clouds and Trace gases Research Infrastructure), their developments which are also at the base for the current ACTRIS Standard Procedures for Aerosol Remote Sensing at ACTRIS Observatories.

ACTRIS also operates mobile facilities, some of them hosting lidar instruments. Applicable protocols are similar as for the ACTRIS Observatories, however with some specificity related to the movement of the instruments in a different environment.

The Atmospheric Radiation Measurement (ARM) user facility is operated by the United States Department of Energy. The ARM facility currently includes six ground-based observatories and has been operating lidars independently from other networks since 1996. In that year, ARM began with the operation of a ceilometer, a micropulse lidar (MPL), and a water vapor/temperature Raman lidar at the Southern Great Plains (SGP) observatory. Today, ARM operates ceilometers and MPLs at each of its six observatories. Raman lidars are currently deployed to three observatories: the SGP, the Eastern North Atlantic (ENA), and the Bankhead National Forest (BNF). ARM also began operating HSRLs in 2010. These HSRLs are in the process of being upgraded to include 1064 nm channels and a wide field of view channel in addition to the original 532 nm channels. The first upgraded system is currently deployed to the SGP. A second system will be deployed to the BNF observatory in 2025 and a new third system is being built for the North Slope of Alaska (NSA).

3.2 ACTRIS protocols (EU)

3.2.1 General protocols

Although the establishment of the ACTRIS ERIC has been concluded in April 2023, several protocols have been issued beforehand to allow the operations of the existing aerosol remote sensing observatories (candidate ACTRIS National Facilities). Statements in these documents follow: 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); c) the EARLINET Single Calculus Chain (SCC) for centralized processing of raw lidar data.

All protocols are inline with the global protocols currently available and described in the GAW report 227, however 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 the 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 has been issued in November 2021 and has been 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 nighttime); e) standard Cimel photometer not older than 15 years; f) continuous operation of the photometer at least during daytime (preferably also lunar measurements during nighttime).

Version 02 of the same document has been issued and published in October 2022. The operation of high spectral resolution lidar has been removed because of the lack of capacity to offer support for QA/QC and data processing. This might be a point transfer of expertise from US to Europe. For details please refer to the document.

3.2.3 Standard operating procedures (SOP) at the station/observatory

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

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 the operation logbook)

Maintenance: Laser; Emission optics; Receiving optics; Filling 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 the QA logbook

Polarization calibration: About the test; Environmental conditions; Test procedure; Schedule; Internal analysis (with example); Filling the maintenance logbook

Rayleigh fit test: About the test; Environmental conditions; Test procedure; Schedule; Internal analysis (with example); Filling the maintenance logbook

Zero bin test: About the test; Environmental conditions; Test procedure (Elastic channels; Inelastic channels); Schedule; Internal analysis (with example); Filling the maintenance logbook

Extended Dark signal measurement: About the test; Environmental conditions; Test procedure; Schedule; Internal analysis; Filling 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 up-taken 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 at a significant scale of these procedures. In most of the cases, lidar calibration is done either by direct comparison with a reference instrument, or by checking the data products.

Our 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 having in-depth knowledge about the instrument in order to keep it well-calibrated. On the other hand, quality check applied on the data products does 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 characterize the instruments at hardware level, and to apply regular tests for checking the stability. The scope of the quality assurance tests described in CARS's 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 analog 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 done regularly by the operators to keep the instrument in its typical performance. Once per year test data is analyzed 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 multiwavelength 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 harmonizing 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, and c) adoption of common signal correction and data processing algorithms.

In case of automatic low-power lidars and ceilometers (ALC), these are standardized instruments for which simple protocols can be applied. Protocols have been developed by E-PROFILE 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 yet not 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 (approximately 280 ceilometers in Europe).

3.3 MPLNET protocols (US)

3.3.1 General protocols

MPLNET (Welton et al., 2001; Welton et al., 2018) utilizes standard instrumentation, calibration, QA/QC, and data processing for all sites in the network. MPLNET currently supports the original MPL (Spinhirne et al., 1995; Campbell et al., 2002), and the polarized MPL and miniMPL (Flynn et al. 2007; Welton et al., 2018). Here we will use the term “MPL” to refer to both the MPL and miniMPL except where explicitly mentioned. All data and on-site calibration measurements are sent to the MPLNET data center at NASA Goddard Space Flight Center (GSFC) using automated hourly data communications. The raw data and calibration files are archived for access by our automated processing system and calibration tools. All calibration analysis, application, QA/QC, and data processing are performed by NASA MPLNET staff on our data center. Calibration analysis includes inspection of the raw calibration data and processing the data to create calibration files, and is the most time consuming MPLNET task. We are exploring options to develop regional calibration centers that would be responsible for performing the calibration analysis. This would remove a significant work load from our NASA staff.

MPLNET data products and our processing system are described on the data center under Product Information. Our product suite includes a collection of signal (Campbell et al., 2002; Welton and Campbell, 2002; Berkoff et al., 2003; Welton et al., 2018), cloud (Lewis et al., 2016; Lewis et al., 2020), aerosol (Welton et al., 2000; Welton et al., 2002), and PBL (Lewis et al., 2013) products. MPLNET product levels follow AERONET V3 conventions, and include near real time (NRT) Level 1 (no QA) and Level 1.5 (QA), and final Level 2 (QA and post calibrations) products. Our NRT processing system generates all Level 1 and 1.5 products hourly using the most recently available calibration files for each instrument. Level 2 processing is done offline and available several months later (for Level 2 aerosol products we are dependent upon Level 2 AERONET data availability). Level 2 products utilize all final calibration files as discussed below. All MPLNET product files are NETCDF4, CF compliant formats and variables include uncertainties derived from raw data and calibration error propagation and additional algorithm uncertainties.

MPLNET lidars require calibrations to accurately transform raw data to the NRB signal product and are shown in Table 4. Publications relevant to our calibration and data processing that are cited here are also provided on the data center.

Table 4 MPLNET Instrument Calibrations

Calibration		Explanation	Lidar
DT	Deadtime	Correction of detector deadtime	MPL, miniMPL
DC	Darkcount*	Subtraction of detector dark noise	MPL
AP	Afterpulse	Subtraction of laser-detector crosstalk noise	MPL, miniMPL
OL	Overlap	Correction for the near range signal loss	MPL, miniMPL
POL	Polarization	Calibration of polarizing optics	MPL**, miniMPL

* not possible for miniMPL, manufacturer provided values used

** only applicable for polarized MPL, all miniMPL are polarized

3.3.2 Protocols for traceability and calibration facilities

The process of calibrating an instrument includes: 1) acquisition of the calibration data, 2) calibration analysis, and 3) applying the calibration to measured atmospheric data (Campbell et al., 2002; Welton and Campbell, 2002; Berkoff et al., 2003; Welton et al., 2018). Step 2, calibration analysis, is the most time consuming and includes inspection of the calibration and processing the calibration data and saving the calibration file. An overview of the calibration process is available on our data center.

Our QA/QC procedures for the NRB signal product include the inspection and processing of the calibration data to ensure calibrations were performed correctly and no poor calibrations are introduced to our processing system. The inspection process includes testing new calibrations on raw data prior to final approval. Our QA/QC procedures also impose standards for the lidar enclosures (including the optical window and its mount) and the environmental controls (instrument temperature, humidity). The final calibrations also create set-points for instrument diagnostics (such as temperature or laser energy) that ensure any data acquired for out-of-bounds conditions are properly flagged. Our NRB product files contain flag variables indicating the status for all calibrations and time indexed flag variables that report any out-of-bounds deviations for measured data relative to each calibration. A final QA NRB flag variable is provided summarizing the final status of each calibrated profile and is also included in all retrieved product files (cloud, aerosol, and PBL) and used for the product specific QA procedures. In addition to the QA flags, in V3 we introduced confidence flags for each product variable that are based on the complexity and maturity of the variable throughout the history of the MPLNET project. For instance, newer variables such as our mixed layer height are deemed low. Our aerosol product variables are flagged according to the nature of the AOD constraint: daytime AERONET AOD, nighttime lunar AOD, or AOD interpolated between AERONET observations using the calibrated lidar to determine an interpolated AOD. Daytime, lunar, and interpolated AOD constrained retrievals are given high, moderate, and low confidence respectively. The

MPLNET aerosol processing methodology is also described in detail on our training page youtube presentation.

MPLNET protocols require the acquisition of DC and AP calibrations at least once every 2 months by on-site staff (on-site SOP is described in section 3.3.3). The OL and POL calibrations are performed prior to field deployment using data acquired at our primary calibration facility at GSFC or at the MPL company prior to shipping to our federated site partners. Once deployed on-site, the OL and POL calibrations are inspected routinely and updated as frequently as required.

The MPL has a very small field-of-view (FOV) to accommodate the eye-safe design of the lidar, resulting in overlaps that are very sensitive to temperature change and movement of optical components. The miniMPL FOV is ~2x larger than the MPL, creating a more stable overlap. However, OL calibration analysis must be performed frequently for both the MPL and miniMPL to track and account for variations. Overlap calibrations are performed utilizing a wide FOV receiver (WFR) (Berkoff et al., 2003) to calibrate the MPL. Most MPLNET sites have WFR installed, thus routine OL calibrations can be performed. For sites lacking WFR, the data must be manually inspected on a routine basis, and results compared to the last overlap calibration. If new OL calibration is required that is performed for clear evenings by fitting higher range overlap curve to molecular atmosphere and utilizing our MPL overlap model to iterate optical parameters until a best fit is achieved. This process is very time consuming and we are in process of installing WFR at all sites in MPLNET.

Polarization calibrations are discussed in Welton et al. (2018) and are the result of procedures based on laboratory inspections of the polarizing optics and measured co and cross polarized signal data while on-site. The POL calibration is done by setting the parameters of the polarizing optics in the MPL (fast axis angles, retardation, extinction-ratio, etc) and calculating the signal bias corrections required to correct the co and cross polarized signals. POL calibrations are typically stable over months to a year, but still require routine inspection. The POL calibration inspection process includes SOP to detect the presence of significant defects in the polarizer which negate the use of our POL calibration process. If detected, the FLC is rejected and must be replaced (this inspection is mandatory during the pre-deployment inspection).

MPLNET protocols require calibration analysis (inspection and calibration processing) to be performed on a rolling 1-2 month cycle. The analysis is performed on all data collected during the preceding 1-2 month cycle, this includes the DC, AP, OL, and POL calibrations. The number of DC and AP calibrations is dependent upon the calibrations performed by on-site staff. The number of OL and POL calibrations is dependent upon inspection of the data and may require frequent (weekly) updates or none at all depending on the stability of the instrument over the 1-2 month cycle. All new calibrations are tested and inspected using measured data. Final calibrations are stored in our database by instrument, with metadata indicating the valid start and end dates of each calibration.

MPLNET NRT processing produces Level 1 and 1.5 data. The NRT processing work-flow uses the most recent, valid calibration files for each instrument. The calibration analysis is performed on a 1-2 month cycle, resulting in Level 1 and 1.5 data having less accurate calibrations applied (most importantly no post calibration analysis over the 1-2 month window). Level 1 and 1.5 data are not reprocessed with final calibrations and should only be used for NRT applications. MPLNET Level 2 processing occurs months later, using all final calibrations, and Level 2 data are considered the final data of record for publications and applications requiring the highest QA.

3.3.3 Standard operating procedures (SOP) at the station/observatory

MPLNET on-site SOP cover a variety of topics and are outlined within our internal documentation. We do not have a published or online copy of our on-site SOP at this time, and plan to resolve this issue soon. Here we summarize our on-site SOP.

Standardized Instrumentation. MPLNET only supports commercial lidars with a proven history of providing high quality data, peer review record, and the ability to operate continuously in automated mode without eye-safety concerns. Further, MPLNET only supports the MPL and miniMPL models at this time due to budgetary restrictions. We are planning intercomparisons and a pilot study to determine if we could support other commercial lidar or ceilometer instruments. But they must meet our existing requirements, have quality calibration processes that are less time consuming then the MPL, and ideally provide increased capability relative to the MPL (e.g. added wavelength channel).

Enclosure Specifications. The MPL must be deployed inside an enclosure that provides environmental controls, physical protection and access control, an optical window port, and data communications. Environmental controls must be capable of controlling humidity and maintaining inside (ambient instrument) temperatures within ± 2 C of a setpoint specified by the MPLNET calibration center responsible for the site (currently this is GSFC for the entire network). The setpoint temperature is determined by the OL calibration and the site climate (the setpoint may be adjusted to warmer temperatures for tropical sites and colder for higher latitudes). The setpoint temperature must be between 15 – 30 C to avoid data quality problems or potential for instrument damage. Typical values are between 20 – 25 C. Interaction between the calibration center and on-site personnel are required to ensure operational temperatures do not deviate out-of-bounds from the setpoint.

Window Specifications. A standard MPLNET window mount must be installed on the enclosure window port. The window mount is designed to reduce mechanical and temperature stress on the optical window from the mount and enclosure, and to reduce afterpulse from window reflections. The window itself must meet MPLNET optical specifications including: BK7 material, transmitted wavefront error < 0.25 waves, fine ground surface finish, anti-reflection coatings for 532 nm, and a minimum clear aperture of 28 cm and thickness of 1.5 cm.

Laser Energy. The laser energy must be maintained within 10% of a setpoint specified by the MPLNET calibration center responsible for the site (currently this is GSFC for the entire network). The energy setpoint is determined from the AP calibration analysis and interactions between the calibration center and on-site personnel are required to ensure operational energies do not deviate out-of-bounds from the setpoint.

DC and AP Calibrations. On-site personnel are responsible for performing DC and AP calibrations at least once every 1-2 months. These actions place the instrument in calibration mode, resulting in loss of atmospheric data during the calibration period. First the enclosure window must be completely covered with an opaque laser safety quality blanket (or hard cover). It is not sufficient to only cover the MPL instrument aperture since AP calibrations must include the optical window. The DC and AP calibrations can be performed once the window is covered. DC calibrations require turning the laser off and measuring the dark count rate of the detector for at least a 10-minute period, ideally 15-30 minutes. AP calibrations require the laser be on at nominal energy, and measuring the afterpulse crosstalk on the detector for at least a 15-minute period, ideally 20 – 30 minutes. After saving the calibration files, the on-site personnel must rename the files by including a .DC. or .AP. element in the file name to discriminate calibration files from atmospheric files. NOTE: the miniMPL design does not accommodate DC calibrations, thus SOP for miniMPL sites only include the AP calibration.

Health and Safety. On-site personnel must be aware of eye-safety and/or outdoor laser use regulations for their region/country. MPLNET personnel provide basic laser safety training and will assist partners with any local eye-safety requirements. The MPL and miniMPL are classified by ANSI as class 1M devices, meaning the laser emission is eye-safe from the instrument aperture (NOHD of 0 meters) for unassisted viewing. However, the MPL and miniMPL exceed the limits of the laser free flight zone in the United States and may have similar issues in other countries. MPLNET SOP is to avoid sites within designated laser free flight zones. In addition to laser safety, on-site personnel are responsible for inspecting the deployed equipment and ensuring it is not damaged or in need of repair. This includes keeping the optical window clean as needed, and utilizing the proper cleaning tools and protocol (provided by the calibration center). On-site staff are required to assist the calibration center with further inspection or testing of equipment if problems arise.

3.4 ARM protocols (US)

3.4.1 General protocols

3.4.1.1 Micropulse lidar

The Micropulse Lidar (MPL) is an eye-safe autonomous elastic-backscatter lidar system operating at 532 nm and is used at all ARM sites to determine the vertical distribution of cloud and aerosol layers. The MPL raw measured signal at any given range is described with the lidar equation (Welton and Campbell, 2002), which contains various terms/corrections that must be applied for accurate retrievals using the MPL data. ARM currently provides its users these corrections (Muradyan and Coulter, 2020) ingested with the b1 level data.

3.4.1.2 ARM Ceilometers:

ARM ceilometers use the Vaisala Model CL31, with BL-VIEW software provided by the vendor to display real-time cloud base altitudes for up to three cloud layers and three potential boundary layer height estimates, along with backscatter intensity profiles. These profiles have a maximum vertical range of 7,700 m and a vertical resolution of 10 m. The data are ingested into the ARM Data Archive following established formatting and file-naming protocols (ARM Data Formatting and File Naming Protocols) and are freely available for download on the ARM Data Discovery website. Automated quality control checks are applied when data streams are processed and are embedded within the data files. Data are scrutinized with automated routines to detect violations of simple physical limits (minimum, maximum, difference), and for some measurements, sophisticated quality algorithms. Values that exceed these criteria are flagged using accompanying variables within the data files, allowing the user to decide which flags to apply to the data.

3.4.1.3 ARM HSRLs:

ARM HSRLs provide absolutely calibrated particulate backscatter coefficient, depolarization, as well as extinction coefficient following the method developed by Eloranta et al. (2018). Data collection and processing are performed by automated routines developed by the University of Wisconsin and are run at ARM Data Center. The data are ingested following ARM data standards. The QC flag for each variable is embedded within the data files.

3.4.1.4 ARM Raman lidars

We note that the ARM Raman lidars are research grade instruments that were specifically developed for the ARM program. All the data acquisition, signal processing and instrument control software were developed by various members of the ARM instrument team over the years.

3.4.1.5 ARM Doppler lidars

The ARM Doppler lidars are commercial-grade instruments that transmit and receive at a single-wavelength (1500 nm). The systems are primarily designed to provide velocity measurements, but they can also measure attenuated backscatter when properly calibrated. Currently a factory calibration curve is used to relate the wide-band SNR, as computed from the Doppler spectrum, to attenuated backscatter. This factory curve corrects for the overlap and is unique to each system that ARM operates. To date we have not evaluated the accuracy of the attenuated backscatter measurements from the ARM Doppler lidars.

3.4.2 Protocols for traceability and calibration facilities

3.4.2.1 ARM MPLs

ARM currently provides its users corrections (Muradyan and Coulter, 2020) ingested with the *b1* level data that are necessary for producing a calibrated signal called Normalized Relative Backscatter (NRB). The NRB is a range corrected, energy normalized signal with all instrument specific corrections applied, except the lidar system constant. Therefore, NRB provides the relative signal strength that can vary based on the instrument optics. ARM currently does not provide a fully calibrated attenuated backscatter that requires the determination of the lidar system constant. Below are details of ARM provided corrections for the NRB calculation and the frequency at which each of these corrections are updated:

Solar background signal (updated continuously). Calculated as the average value at the end of the signal region and reported per each time stamp.

Overlap Function (updated with repairs or "as needed" at mobile facilities). The MPL near-range signal returns are complicated by the instrument's overlap range, which is the minimum distance at which returning signals are completely in the instrument field-of-view. The overlap correction as a function of height accounts for the loss in the near-field receiver efficiency.

- *Vendor-provided overlap*: Calculated from co-located simultaneous measurements from the MPL and the vendor's "gold standard" instrument, sampling the same column of air. Provided to ARM only with instrument repairs.
- *Wide Field Receiver (WFR):* To add in-field overlap correction capability, ARM deploys WFRs at its two

mobile facilities. These sit on top of the MPL telescope, sampling the same column of the atmosphere as the MPL. These measurements are then used to calculate the overlap function according to Berkoff et al. 2003 on an as-needed basis.

Dead-time Correction (updated with a new detector). Detector dead-time effect is caused by saturation of the detector signals at high count rates. When the detector is saturated, the displayed count rate is lower than the actual count rate, resulting in a non-linear relationship between the two rates. A lookup table is created by the detector vendor to correct for the detector's non-linear behavior, and it is provided to ARM when a new detector is acquired.

Afterpulse Correction (updated quarterly). Afterpulse measurements are collected at all ARM sites every quarter to account for the detector noise induced from the firing of the laser. The measurements are taken by covering the instrument transceiver to eliminate all light sources, and collecting the measurement for 45 minutes. The quarterly average afterpulse profile is then made available to ARM users via the ingested b1 level data.

Dark Count (updated quarterly). These are the counts related to the instrument noise (is present in the afterpulse measurement as well) and it's calculated as the average of the 15-min measurements of noise collected when the laser is turned off.

3.4.2.2 Ceilometers

Calibration can be verified by tilting the ceilometer toward a hard target at a known distance. This test involves removing the measurement unit from its shield, positioning it horizontally, disabling the tilt angle correction, and detecting the return signal from a solid object located at least 300 m away. The calibration of the ceilometer's laser transmitter is checked annually to ensure a range resolution of 10 m. Additionally, given ARM's extensive array of lidars and radars at each facility, comparing ceilometer data with MPL heights during low-cloud conditions can provide valuable insights.

3.4.2.3 ARM HSRLs

HSRL can measure both total backscatter and molecular backscatter. The absolute calibration is generated by comparing the observed molecular lidar return to the lidar return computed from Rayleigh scattering theory. Details of the absolute calibration are described by ARM HSRL handbook.

3.4.2.4 ARM RLs

Ground bin. The ground bin is the range gate corresponding to a range of zero. On each pulse the system records several micro-seconds of pre-trigger data. The ground bin is determined from the location of the initial spike in the elastic signals that occurs as the pulse leaves the telescope. Determination of the ground bin is performed from analysis of the photon counting signals and the values are saved in a configuration file that is used by the value-added product (VAP) processing software. These values are updated whenever a major change occurs to the lidar.

Analog voltage delay. The analog signal exhibits a small delay relative to the photon counting signal. This delay is a fixed property the data recorder and results in a signal that is shifted by several range bins. The delay is determined in post-processing by shifting the analog signal to get the best correlation with the photon counting signal. The analog voltage delays for each detection channel are stored in a configuration that is accessed by the VAP processing software. These values are updated whenever a Licel unit is reconfigured or replaced.

Pulse pileup. Pulse pileup or “deadtime” corrections are performed on the photon counting data. This correction accounts the nonlinearity that occurs at higher irradiances due to pulse pileup effects. The deadtime correction parameters for each detection channels are determined through off-line analysis and stored in a configuration file that is accessed by the VAP processing software. These values are updated whenever a PMT or Licel unit has been reconfigured or replaced.

Dark counts. The system records several seconds of noise background data at the top of each hour. These data are used to characterize the noise background and any range dependence it may have.

Gluing. The analog voltage and photon counting signals are combined to produce a signal with improved dynamic range. This process has been referred to as “gluing.” The process we follow has been published in the literature. The basic idea is to form a “merged” signal that uses the photon counting data at low irradiance and the analog voltage data at higher irradiances. This requires that the analog voltages be scaled and shifted to best match the photon counting data. This is accomplished using a linear regression analysis between the photon counting and the analog voltage data. This analysis is conducted over a range of light levels in which both the photon counting data and analog voltages are linear. For the ARM Raman Lidar the regression is done using photon counting rates are between 1 and 15 MHz. The results of the regression analysis are used to convert the analog voltage to equivalent photon counts. The glued signal is formed such that photon counting rates are used below 10 MHz and the scaled (and shifted) analog data are used for light levels above 15 MHz. A linear combination of the two signals are used between 10 and 15 MHz.

Range dependent background. As a final signal processing step, it may be necessary to correct for any significant range dependence of the background.

Backscatter. The ARM Raman lidar produces estimates of aerosol backscatter using the elastic (355nm) and N2 (387nm) merged photon counting rate signals. Air density profiles are also needed to estimate molecular backscatter and extinction. At the ARM sites these profiles are computed from either 2x or 4x daily radiosonde data. The radiosonde data are linearly interpolated to the sample times of the Raman lidar.

Background Subtraction. The background or DC level is subtracted from the wide- and narrow-FOV elastic and N_2 signals. The background is computed from the pre-trigger (z<0) portion of the profiles. Currently it is treated as a constant, i.e. no range dependence.

Overlap corrections. Overlap corrections are applied to the N_2 and elastic signals. Overlap correction profiles are determined through off-line analysis and stored in a configuration file that is used by the VAP processing software.

Unpolarized elastic signal. The ARM Raman Lidar has two orthogonally polarized elastic channels that are used to compute linear depolarization ratios. For backscatter calculations these two signals are combined to create an unpolarized signal. This requires that the differential gain between the two channels be equalized. This is done using a scaling parameter on the depolarization signal. The scaling or gain parameter is determined through off-line analysis and stored in a configuration file. It is updated whenever a change occurs to the narrow-FOV elastic and or depolarization detection channels, including the Licel data recorders.

Angstrom exponent. An estimate of the Angstrom exponent is required to relate the extinction at 355 nm to the extinction at 387 nm. The Angstrom exponent is derived from off-line analysis of sun photometer data and stored in a configuration file that is used by the VAP processing software.

Calibration. The narrow-FOV ASR values are scaled such that ASR = 1 in clean aerosol-free layers. The wide-FOV ASR is scaled to match the narrow-FOV ASR over a height layer with mutually valid data. Aerosol backscatter is then estimated from (ASR-1)beta_mol, where beta_mol is the molecular volume backscatter coefficient computed from radiosonde data.

Merging Fields-of-View (FOV). The narrow- and wide-FOV ASR profiles are merged within the lowest 1 km. The merged profile transitions from purely wide-FOV data at the bottom of the profile to purely narrow-FOV data at roughly 1 km AGL.

3.4.2.5 ARM DLs

Overlap. Since most of the ARM Doppler lidars have full scanning capability it is possible to estimate the overlap by pointing the beam horizontally and acquiring data during periods when the extinction and backscatter are approximately constant along the path. A regression analysis on the logarithm of the range-corrected signal in the region of complete overlap yields estimates of the extinction and scaled backscatter. The overlap function is estimated from the ratio of the observed range-corrected signal with the prediction based on the retrieved backscatter and extinction. This test has not been a routine part of ARM operations.

Attenuated backscatter calibration. Calibration of the overlap-corrected backscatter would require using a target whose volume backscatter coefficient is known. This may be possible using horizontal staring data and surface disdrometer measurements at the ARM site, but this has not been part of normal ARM operations.

Heading calibration. The heading calibration determines the lidar's orientation relative to true north. This done by performing a low-elevation-angle sector scan in the direction of a target of opportunity, i.e. power pole or narrow feature that is several hundred meters from the lidar. The lidar's heading is then determined from the known positions of the lidar and target. This test can also be used to assess the accuracy of the range. Heading calibrations are routinely checked an updated as needed. These calibrations are maintained in a configuration file that are used by the ingest.

Radial velocity bias. Bias in the radial velocities are assessed by directing the beam at a hard target that is several hundred meters from the lidar. The results should give a mean value of 0 ms-1 to within a standard deviation of <10 cm s^{-1}.

Flip test. This test is done to determine the alignment of the outgoing beam relative to the apparent pointing direction as indicated by the scanner motor position. This test requires targets that are vertically and horizontally oriented and several hundred meters from the lidar. Ideally, this test is done upon receipt of a new system. The idea behind the flip test is that the beam pointing direction should be unaffected by rotating the scanner from (az, el) to (az+180°,180°-el). In practice, the beam is seldom perfectly aligned with the scanner boresight, so the beam direction will change slightly as a result of the rotation. To determine the azimuth offset we perform a sequence of two high-resolution low-elevation PPI sector scans in the direction of a narrow isolated feature such as a power pole. The first scan is not flipped and the second scan is flipped. When analyzing these scans, the target returns will, in general, be shifted slightly. For one of the ARM Doppler lidars (S/N 09) we found an azimuth offset of -0.19° and an elevation offset 0.04°. These values are consistent with the vendor's quoted pointing accuracy.

3.4.3 Standard operating procedures (SOP) at the station/observatory

3.4.3.1 ARM MPLs

The ARM MPLs consist of a single assembly transceiver unit, a laser controller and an MPL data system/computer that runs the latest version of the SigmaMPL software. As the window that MPL sits under affects instrument polarization, ARM has conducted an extensive glass properties effect on MPL signal evaluation (including thermal and stress evaluation) and has been using 0.6'' thick BK7 optical flat (1-wave transmitted wavefront error) windows at all sites since 2019, with anti-reflective coating for 532 nm. The MPLs are fully autonomous and uses the SigmaMPL software for configuration and data logging. The ARM site operators perform preventative maintenance to keep the MPL dust free and clean the window daily. ARM also utilizes IR heater assembly from outside of the window to prevent condensation and precipitation accumulation.

3.4.3.2 ARM Ceilometers

The ceilometer is an automated, low-power system with standardized protocols for operation. Proper operation of the CL31 model is verified according to guidelines provided in the VAISALA CL31 User guide. At each ARM observatory, technicians perform daily preventative maintenance on the instruments following procedures outlined by the instrument mentor, who also conducts weekly reviews of plots from the ceilometer data. If any issues are identified, the instrument mentor drafts a Data Quality Report (DQR), detailing the data quality for a specific datastream and time range, along with a severity rating for the issue. When users request ARM data through the Data Discovery platform, all relevant DQRs for the ordered datastreams are included with the data order.

3.4.3.3 ARM HSRLs

All components of the HSRL are located on a single assembly. Once the instrument is in place beneath a suitable window, operation can begin simply after establishing power and Ethernet connections. All start-up and calibration procedures are performed by the onboard computer and can be controlled remotely. The only manual function required by the operator is to cover the output of the telescope during a specified period of the otherwise-automated calibration procedure. The system operation is fully automated using software relevant in the HSRL processor. Similar to other ARM instruments, technicians perform daily preventative maintenance. DQRs are issued if any issues are identified.

3.4.3.4 ARM RLs

Detailed information on ARM RL description, specifications, and data can be found in RL instrument handbook (Newsom, Bambha and Chand, 2022).

3.4.3.5 ARM DLs

Detailed information on ARM DL deployment locations, standard operating procedures and scan types can be found in the DL Instrument Handbook (Newsom and Krishnamurthy, 2022).

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