Deliverable 2.3: Recommendations for common calibration and operation procedures

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Preamble

The main objective of CARGO-ACT is to pave the way for global interoperability that will ultimately lead to more harmonized global datasets of key atmospheric parameters, specifically for short-lived components such as aerosol particles, trace gases, and clouds. Beginning with documenting protocols of existing networks (Milestone #4) followed by the identification of opportunities for harmonization (D2.1), we have assessed which procedures can be harmonized across the networks. This deliverable presents the results of these assessments in a form of Recommendations for common calibration and operation procedures focused on key atmospheric parameters as proof of concept.

1 Recommendations for measurements of aerosol in-situ (IS) variable

The following recommendations are the results of deliberations between the participating IS networks of the different protocols employed (see D2.1 for detailed descriptions of the networks) in terms of measurements of the four aerosol IS variables listed in Table 1. The networks are:

- ACTRIS (EU): Aerosol, Clouds and Trace Gases Research Infrastructure;
- NOAA NFAN (US): National Oceanic and Atmospheric Administration - Federated Aerosol Network;
- GAW (global): Global Atmospheric Watch;
- DOE-ARM (US): US Department of Energy - Atmospheric Radiation Measurement fixed and mobile observatories;

and to some extent,

- ASCENT (US): Atmospheric Science and Chemistry Measurement Network

Table 1 List of aerosol IS microphysical and optical variables and relevant measurement principle.

IS Variables	measurement methods/instrumentation
particle number concentration Dp > 10 nm (PNC)	condensation particle counters (CPC)
particle number size distribution (10-800 nm) (PNSD)	mobility particle size spectrometers (MPSS)
particle light scattering coefficient (Scat)	integrating nephelometers (IN)
particle light absorption coefficient (Abs)	absorption photometers (AP)

1.1 General recommendations

Sampling, Losses & Conditioning

- An impactor with at least a PM_{10} cut off should be used for the instruments.
- A whole air inlet is recommended for observatories which are in cloud more than 10% of the time.
- Conductive tubing such as stainless steel must be used as inlets.
- The sampling lines should be as short as possible with no sharp angles and minimal bends to minimize losses by diffusion and impaction, respectively.
- Vertical tubing is recommended for sampling of coarse mode particles to avoid particle settling in horizontal pipes.

- The aerosol sample must be kept at a relative humidity (RH) of less than 40% to ensure comparable measurements and to avoid the influence of liquid water on the variables
    - The method of keeping the RH below 40% should be documented.
- The volumetric flow rate at the inlet of the instrument must be either monitored or frequently measured.
- The current pressure, temperature, relative humidity must be measured with a time resolution of 5 minutes or better.

1.2 Particle number concentration (PNC)

The recommendations presented here are for PNC measured using condensation particle counters (CPC) and were adapted from the EN 16976:2024, ISO 27891:2015 and Wiedensohler et al., 2018, modified based on the harmonization assessment of D2.1 by the participating networks.

1.2.1 Technical requirements

The only technical requirement recommended here is that the CPC should cover concentrations of at least 3 orders of magnitude. The rest of the technical requirements need further investigations regarding their feasibility depending on network needs. Examples are given below.

Working fluid: Most networks use a CPC with n-butanol as a working fluid. However, water-based CPCs are becoming more common and other fluids (Weber et al., 2023) are being explored. We recommend a comprehensive analysis of the comparability of CPCs with a different working fluid to butanol-based CPCs in terms of performance, traceability, and sustainability.

Dp50: This should be defined by network, but we do recommend harmonizing the Dp50 within the network. If the Dp50 differs from one network to another, we recommend that networks report the Dp50 value in the metadata.

1.2.2 Facility calibration set-up and procedure

Facility set-up

- The laboratory conditions of the calibration facility must be maintained between 20 and 30 degrees Celsius.
- The primary standard for the counting efficiency is a Faraday Cup Aerosol Electrometer (FCAE) which has been calibrated and certified by a recognized metrological institute/agency.

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- The secondary standard is a stand-alone total CPC (T-CPC) calibrated against the primary standard.
- The standard material is spherical silver particles evaporated/condensed at 600 degrees Celsius in a sintering oven/furnace with nitrogen as a gas medium.
- A size selecting rack using a classifier is required.

Facility calibration procedures

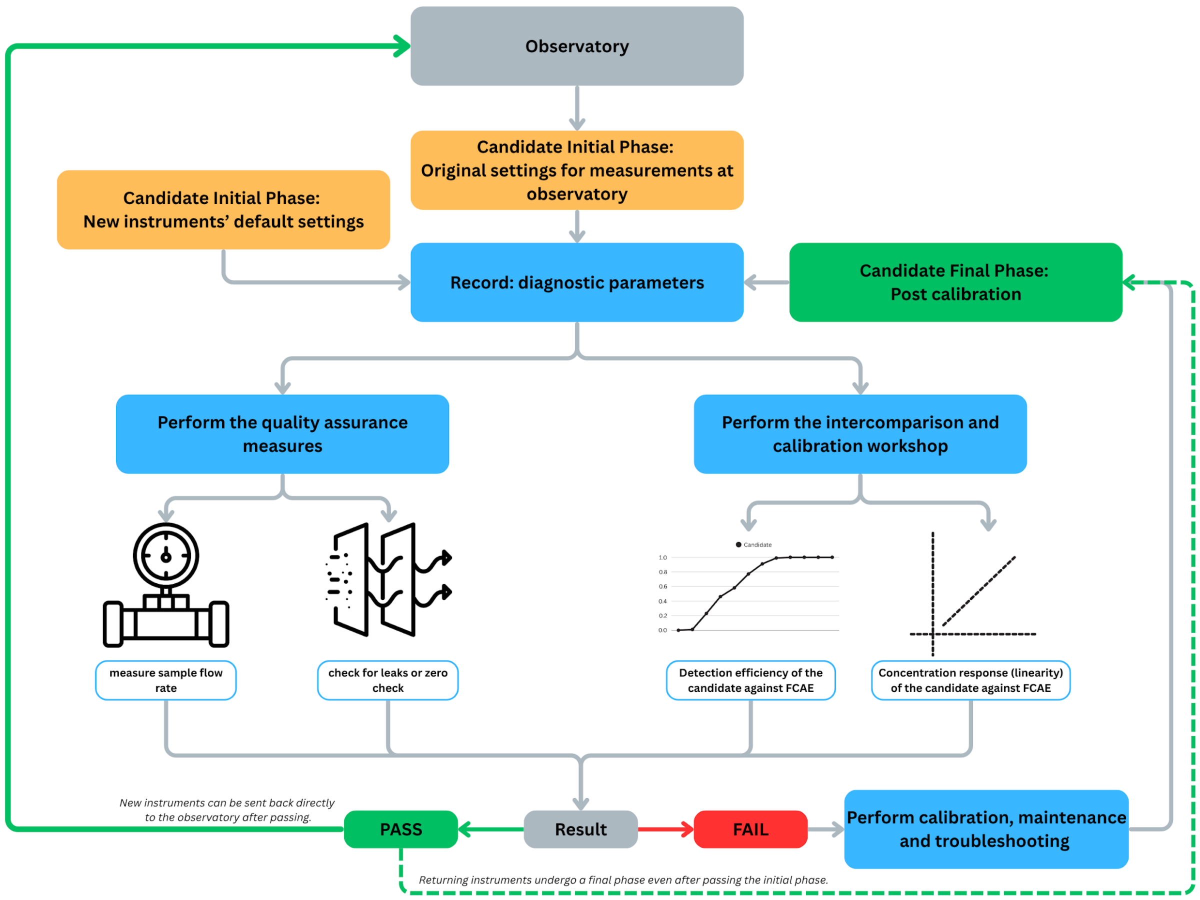

Figure 1 Schematic diagram of the recommended calibration and intercomparison procedures performed at the facility for the measurement of PNC using a CPC.

1. The instrument must be checked twice: 1) Initial phase - with original observatory operational setup, and 2) final phase - after calibration and/or troubleshooting.
2. For both phases, the diagnostic parameters must be recorded.
3. Perform the following instrument checks:

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   a. Flow rate: calibrated flow rate should have a <=5% difference to the nominal flow rate
   b. leak check or zero check: this should be done by placing a HEPA filter on the inlet for 60 minutes (full zero check) where the counts should be < 1 min–1 .

4. Connect the candidate, FCAE, and reference CPC in the same manifold.
5. Perform the intercomparison and calibration workshop tests (initial and final phases) for the following performance characteristics:
   a. Detection efficiency*: Generate silver particles with concentrations level where coincidence is <1%. Select several sizes with the following criteria:
      i. 1 point at the plateau (40 nm)
      ii. 1 point at the network-specific Dp50
      iii. 1 point (1 nm) above and below the Dp50
      iv. 1 point at 90% efficiency
      v. 1 point where detection is close to zero

      The detection efficiency is the ratio between the concentration measured by the FCAE and the candidate CPC. The detection efficiencies at low particle sizes and at the plateau should be within the allowable uncertainty ranged defined by the network.
   b. Concentration response: generate nominally spherical silver particles sized 40 nm. Test the response of the instrument for several concentration levels from 1000 to 100 000 particles/cm3 or until the response is linear with an uncertainty of 10% with minimum 5 points in between. Compare the response of the candidate CPC against the FCAE using linear least squares regression analysis. The slope of the linear fit should be within the allowable uncertainty range defined by the network.

*Note: Currently, for the fitting of the CPC efficiency curve, an empirical equation is used/recommended by GAW and CEN. However, further studies are needed to derive a new equation more appropriate for new generations of CPCs.

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1.2.3 Standard operating procedures (SOPs) at the observatory

The following recommendations are for stand-alone T-CPCs running in an observatory either only for measurements of total PNC or also in parallel with an MPSS as a quality control measure: PNC closure. In this case, the T-CPC should not be used for other purposes to avoid contamination.

1. Prior to installation, the CPC should undergo a calibration and intercomparison workshop in a calibration centre. For technical troubleshooting, the instrument should be sent back to the manufacturer and then to the calibration facility for quality assurance checks. The frequency of facility calibration and intercomparison should be harmonized within the network.
2. Perform the following quality control measures at least once a month:
   - sample flow rate
   - leak check or zero check
   - level of operating fluid (more frequent)
   - data acquisition (more frequent, automated check or flagging if possible)
   - wick check, cleaning, or replacement (frequency station dependent, but wick check should be done at least every 6 months)
3. Record the diagnostic parameters such as (but not limited to):
   - RH, temperature, and pressure at the inlet
   - nozzle pressure at the inlet to the optical cell
   - critical orifice pressure
   - laser current

1.3 Particle number size distribution (PNSD)

As proof of concept, these recommendations are for PNSD with size range 10-800 nm measured using a mobility particle size spectrometer (MPSS). These were adapted from the CEN/TS 17434:2020, ISO 15900:2020 and Wiedensohler et al., 2018, modified based on the harmonization assessment of D2.1 by the participating networks.

1.3.1 Technical requirements

The following are recommendations for instrument technical requirements:

- A lower detection diameter of 10 nm is recommended. If another detection limit is used, we recommend harmonizing it within the network and reporting it in the metadata.

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- Bipolar diffusion charger: radioactive sources (Kr85 and Ni63) are recommended. X-ray could be also used depending on the network specifications if the specific bipolar charger equilibrium is known.
- Polarity of the classifier: networks can use either positive or negative, however, this must be harmonized within the network
- Particle size resolution: 16-32 bins/decade
- Time resolution: 5-10 minutes

1.3.2 Facility calibration set-up and procedure

Facility set-up

- The laboratory conditions of the calibration facility must be maintained between 20 and 25 degrees Celsius.
- The primary standard for the particle number concentration (PNC) is a Faraday Cup Aerosol Electrometer (FCAE) which must be frequently calibrated and certified by a recognized National Metrology Institute.
- Certified polystyrene latex particles (PSL) must be used to determine the correct sizing of an MPSS. We recommend including monodisperse PSL around 200 nm to avoid the water peak and make the doubly and triply charged particles visible.
- Ambient air should be preferably used for intercomparisons of MPSS. Ammonium sulfate (AS) might be used as well for more specific concentrations and diameters providing a deeper analysis of biases per size bin. However, it must be assured that the AS aerosol is in the bipolar charge equilibrium.
- For the MPSS calibration setup: larger particles must be avoided and the flow inside sampling lines must be laminar to achieve stable number concentrations.
- The relative humidity of the aerosol sample must be kept at less than 40%. All techniques (Nafion drying, sample heating) are allowed except for bundle drying.
- Volumetric flow rates must be measured using a flow meter which has been calibrated and certified by a National Metrology Institute.

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Facility calibration procedures

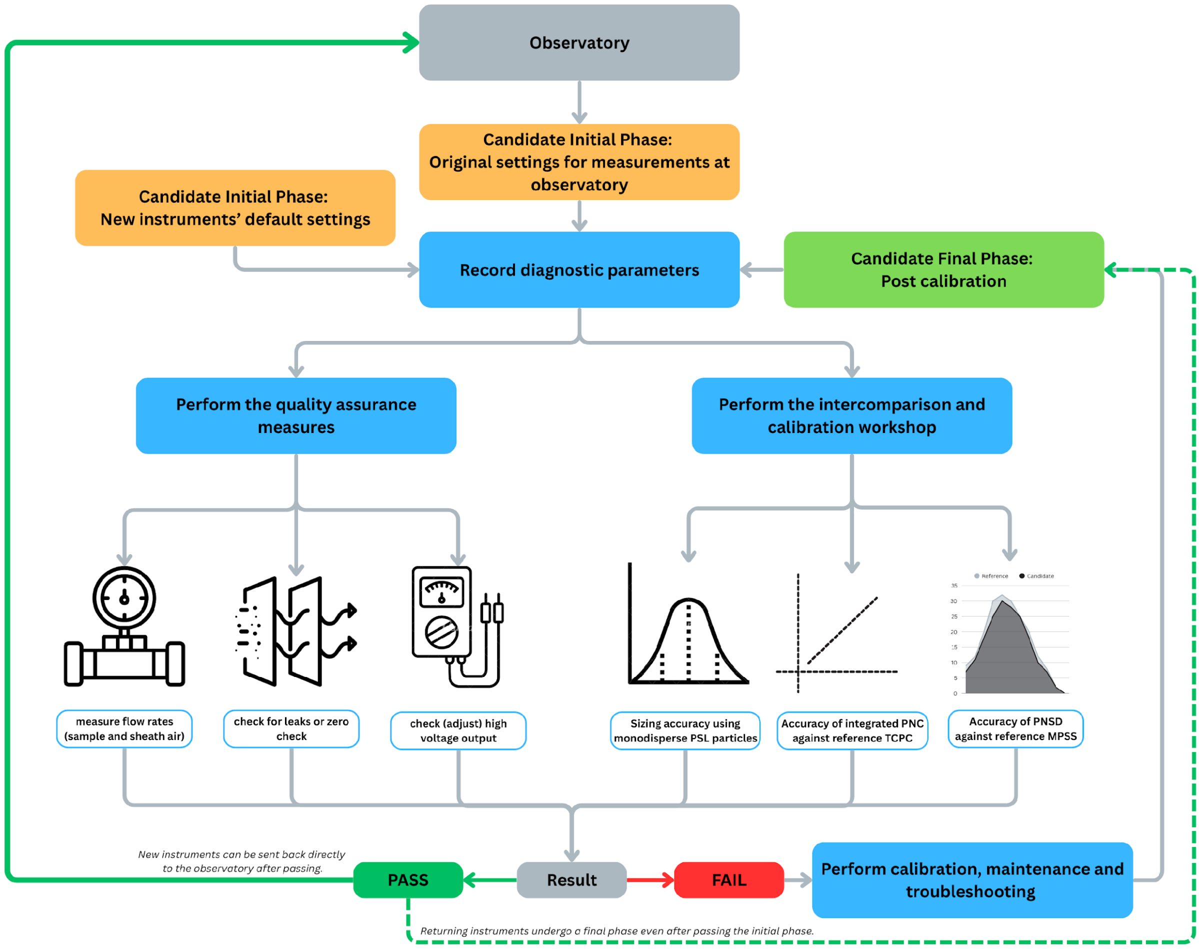

Figure 2 Schematic diagram of the recommended calibration and intercomparison procedures performed at the facility for the measurement of PNSD using an MPSS.

1. The MPSS must be checked twice: 1) Initial phase - with original station operational setup, and 2) final phase - after calibration and/or troubleshooting.
2. For both phases, the diagnostic parameters must be recorded.
3. Perform the following instrument checks:
   - volumetric flow rates (sample and sheath air): measure the flow rates using a certified and calibrated flow meter. The calibrated flow rate should have a <=5% difference to the nominal flow rate.

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- leak check or zero check: Sample particle free air by placing a HEPA filter on the inlet of the instrument for minimum 4 scans (depending on the instrument). The integral PNC should be <5 particles/cm^3.
- If possible, the high voltage output of the MPSS should be checked for allowable voltages using an appropriate voltmeter. Follow the procedure in the instrument manual on how this should be done safely.
- If possible and necessary, perform a high voltage adjustment calibration. Follow the procedure in the instrument manual on how this should be done safely.

4. Perform the intercomparison and calibration workshop tests (initial and final phases) for the following performance characteristics:
   - Particle size calibration accuracy test: Nebulize certified PSL particles of known sizes. The peak of the mode should be within 3% of the nominal size(s).
   - Accuracy of the integrated PNC of the instrument: This is a closure between the total PNC measured by the reference T-CPC and the measured PNC of the instrument integrated from 10-800 nm. The reference MPSS and reference T-CPC must be in the same manifold as the candidate MPSS and sampling ambient air for at least 8 hours. The difference between the candidate and both references should be within the allowable uncertainty range required by the network.
   - Accuracy of the PNSD: The PNSD of the candidate is compared against the reference MPSS across all sizes. The difference between the candidate and the reference should be within the allowable uncertainty range required by the network.
5. Instrument is returned to the observatory and re-installed.

1.3.3 Standard operating procedures (SOPs) at the observatory

1. Prior to installation at an observatory, the MPSS should undergo a calibration and intercomparison workshop at a central calibration facility. For technical troubleshooting, the instrument should be sent back to the manufacturer and then to the calibration facility for quality assurance checks. The frequency of calibration and intercomparison at a central facility should be harmonized within the network.

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2. Check the laboratory or observatory conditions: the MPSS should be in controlled conditions of temperatures between 20-30 degrees Celsius. In the summertime, to avoid condensation inside the tubes, the temperature can be closer to 30 degrees Celsius.
3. Perform the following checks at least once a month:
    - aerosol flow rate
    - sheath air flow rate
    - leak check or zero check
    - sizing check: at least 1 size of nebulized PSL particles
    - high voltage check if possible
    - data acquisition - data is being acquired from instrument (more frequently, preferably with automated flagging)

1.4 Particle light scattering coefficient (Scat)

The recommendations presented here are for Scat measured using integrating nephelometers (IN) adapted from WMO/GAW Report No. 227 and Ogren et al., 2017 modified based on harmonization assessment of D2.1 by the participating networks.

1.4.1 Technical requirements

The following are recommendations for instrument technical requirements:

- multi-wavelength integrating nephelometer
- has the capability to be calibrated using two gases
- can automatically perform baseline measurements at regular intervals
- has a response time of <5 minutes
- time resolution of <= 1 minute
- truncation correction scheme should be reported in the metadata

1.4.2 Facility calibration set-up and procedure

Facility set-up

- standard material: gas with known scattering coefficient, usually CO_2 gas with 99.9% purity with no dip tube and no helium headspace
- secondary standard (optional): master IN for intercomparisons

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- For intercomparisons, ambient air and nebulized ammonium sulfate can be used

Facility calibration procedures

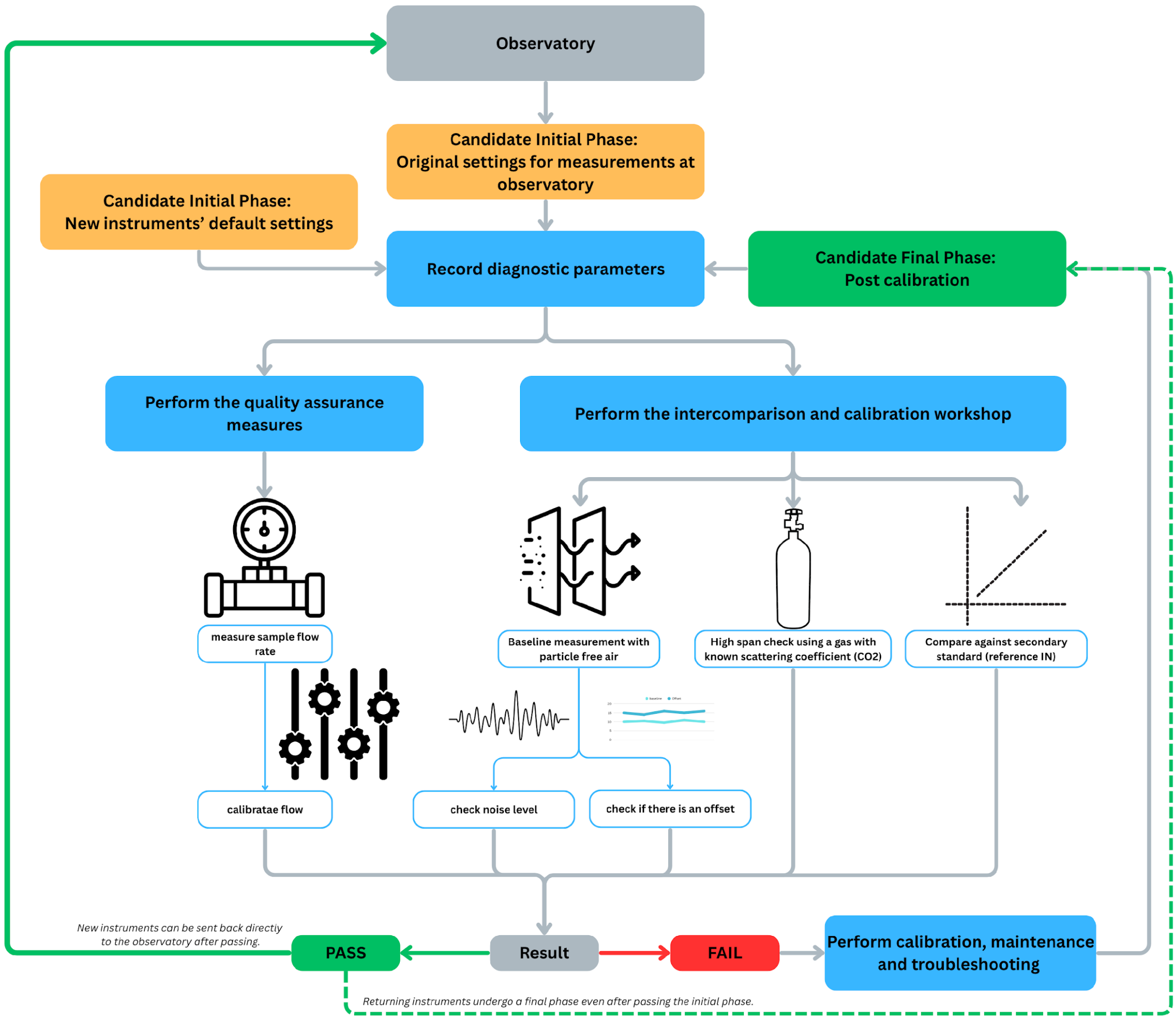

Figure 3 Schematic diagram of the recommended calibration and intercomparison procedures performed at the facility for the measurement of Scat using an IN.

1. The instrument must be checked twice: 1) Initial phase - with original observatory operational setup, and 2) final phase - after calibration and/or troubleshooting.
2. Record status values and measure sample flow rate.

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3. Perform baseline measurement by operating the device with particle free air for a pre-determined amount of time.
    - the noise (standard deviation) should be < 0.5Mm-1 for 1 minute sample time
    - the offset should be < 0.5 Mm-1 for 1 minute sampling time (average over 1 minute)
4. Perform a high span check using a gas with known scattering coefficient for a minimum of 1 hour with at least 6 L/min flow.
    - The deviation between the measured Scat and the primary reference should be within the allowable uncertainty range.
5. Additionally, check the accuracy of the IN against optical reference using ammonium sulfate or another purely scattering aerosol.
    - The deviation of the candidate from the reference IN should be within the allowable uncertainty range.

1.4.3 Standard operating procedures (SOPs) at the observatory

1. Perform basic checks and calibrations (flow, gas check) prior to deployment. When possible, send to a calibration facility for calibration and instrument intercomparison.
2. Perform the following quality control measures:
    - monitor and check lamp health, replace if necessary
    - check the cleanliness of the optics
    - boundary checks
    - check the noise level (mean and standard deviation while measuring filtered air)
    - check the offset (mean of the measurements after some time while measuring particle free air)
    - measure the sample flow rate
3. Perform the following:
    - span check with a gas of known scattering coefficient at least once a month
    - baseline check (e.g., 'zero') with particle free air at least once per day. At baseline stations with low particle light scattering, the zero must be performed hourly to obtain an accurate molecular scattering.
4. Record the following diagnostic parameters
    - T, RH, and P in the cell

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- count rates (Hz)
- background (zero) values

1.5 Particle light absorption coefficient (Abs)

The recommendations presented here are for Abs measured using filter-based absorption photometers (AP), particularly the aethalometers adapted from WMO/GAW Report No. 227 Mueller et al., 2011, and Petzold et al., 2005 modified based on the harmonization assessment of D2.1 by the participating networks.

1.5.1 Technical requirements

Harmonization for the sake of requiring technical specifications for filter-based absorption photometers (AP) used in the different networks is challenging due to the diversity of photometers and the types of filters used. Therefore, the following technical requirements are for networks using aethalometers which is the most common instrument currently. It is highly recommended to perform investigations on the comparability of the different absorption photometers with each other, against the reference method, as well as the impact of the different filter types to derive harmonization factors which can be used across networks.

1.5.2 Facility calibration set-up and procedure

Facility set-up

- Primary standard: extinction minus scattering (EMS) requires a reference instrument measuring scattering coefficient
- secondary standard: reference filter-based absorption photometer
- standard materials: graphite and soot
- requires soot and particle generators

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Facility calibration procedures

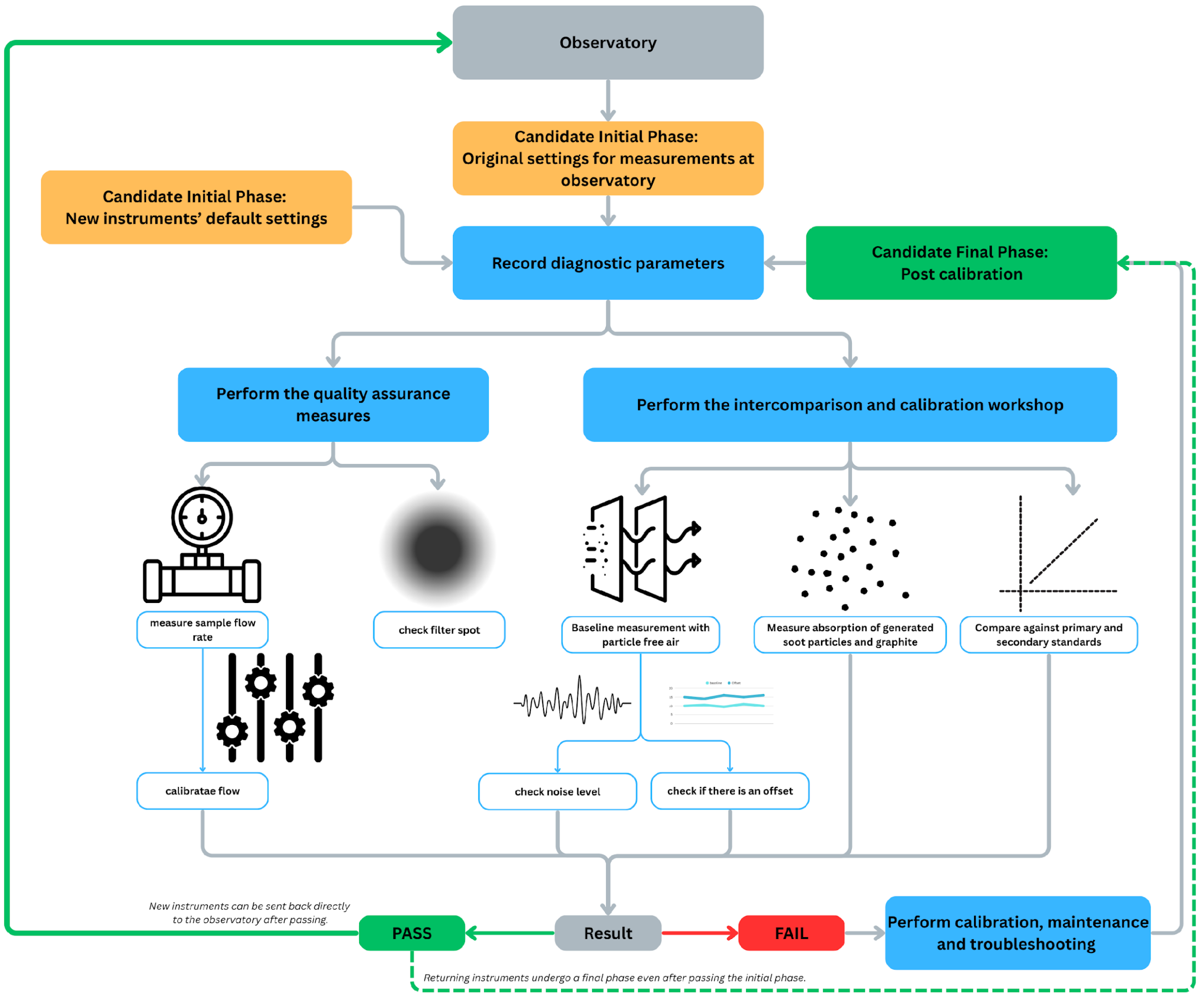

Figure 4 Schematic diagram of the recommended calibration and intercomparison procedures performed at the facility for the measurement of Abs using an FAP.

1. The instrument must be checked twice: 1) Initial phase - with original observatory operational setup, and 2) final phase - after calibration and/or troubleshooting.
2. Record status values
3. Check the particle loaded spot on the filter (visual check)
4. Measure the sample flow rate: it should be within the allowable uncertainty range.
5. Perform baseline measurements (zero check) with particle free air.
    - the noise (standard deviation) should be < 0.5Mm-1 for 1 minute
    - the offset should be < 0.5Mm-1 for 1 minute sampling time offset from zero

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6. Perform an accuracy test by comparing the Abs measured by the candidate against the reference method EMS using graphite and generated soot particles. Measurements should be done for a minimum of 3 hours for each test aerosol with at least 3 tape advances. The deviation should be within the allowable uncertainty range.
7. Perform an accuracy test by comparing the candidate against the reference instrument (secondary standard). The deviation should be within the allowable uncertainty range.
8. Perform a flow calibration, when necessary (following instruction manual), then repeat steps 5-7.

1.5.3 Standard operating procedures (SOPs) at the observatory

1. Perform the following quality control measures at least once a month:
    - measure the sample flow rate
    - check sufficiency of the filter tape length
    - check the filter spot for any irregularities
2. Perform baseline/leak check or zero check (every 6 months)
3. Perform flow calibration when necessary

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2 Recommendations for measurements of aerosol remote sensing (RS) variables

2.1 Introduction- Remote Sensing (RS) Variables

CARGO-ACT: **Cooperation and AgReements enhancing Global interOperability for Aerosol, Cloud and Trace gas research infrastructures** focuses on four aerosol remote sensing variables, which can be measured with various lidar techniques. Lidar types which are considered in CARGO-ACT for potential harmonization are marked in bold, Table 1. Lidar types and codes are taken from GALION Data and Instrumentation, where mapping to the WIGOS metadata standards is provided [note that instrument options can include combinations from more than one standard by using an _ separator; e.g. a polarised ceilometer would use "CL_PL" and those using co-located sunphotometers for retrievals would add "_SP"]. 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. Definition of RS variables, Table 2, is taken from ACTRIS Vocabulary.

Table 2 List of instrument types and codes. In bold, lidars considered in CARGO-ACT for potential harmonization.

GALION 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 Absorption Lidar	320	Integrated path differential absorption (IPDA) lidar
PL	**Polarized Lidar**	**pending**	**pending**
MPL	**Micro-pulse Lidar**	**pending**	**pending**
miniMPL	**Mini Micro Pulse LiDAR**	**pending**	**pending**
MWBL	**Multi-Wavelength Backscatter Lidar**	**341**	**Backscatter lidar**
MWRL	**Multi-Wavelength Raman Lidar**	**143**	**Raman lidar**
MWHSRL	**Multi-Wavelength High Spectral**	**342**	**High spectral resolution (HSR) lidar**

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	Resolution Lidar		
MWPL	**Multi-Wavelength Polarized Lidar**	**pending**	**pending**
SP	Sunphotometer or Sun-Sky Photometer	244	Sun-tracking photometry

Table 3 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, DWL
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, DWL_PL
Aerosol layer geometrical properties: • Aerosol layer base altitude • Aerosol layer top altitude	CL, BL, RL, HSRL, MWBL, MWRL, MWHSRL, DWL, DIAL, IPDIAL

Atmospheric lidar measurements around the world can differ in terms of scientific goals between and within measurement networks, necessitating careful consideration of atmospheric variables covered. For our documentation, we examined the variables covered by the following networks in the EU and USA in relation to the RS variables listed in Table 3 .

- ACTRIS (the Aerosol, Clouds and Trace gases Research Infrastructure) (EU);
- MPLNET (NASA Micro-Pulse Lidar Network) (US);
- Atmospheric Radiation Measurement (ARM) user facility (US) fixed and mobile observatories;

GALION (GAW Aerosol LIdar Observation Network) is a global network of lidar networks designed to coordinate activities and provide detailed global profiling of atmospheric aerosols and clouds. It is critical in connecting regional and global aerosol lidar networks while also advocating for harmonization of 1) lidar data products, 2) observation methods, 3) calibration and QC/QA, and 4) processing techniques. Topics 1-2 have seen progress, and CARGO-ACT is built on GALION vocabularies and instrument methodology. However, GALION harmonization of topics 3–4 across all networks is underway. CARGO-ACT will establish a framework to achieve these goals in collaboration with ACTRIS, MPLNET, and ARM, thereby supporting GALION objectives.

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MPLNET is a global federated network of Micro-Pulse Lidar (MPL) systems that measure the vertical structure of aerosols and clouds, as well as boundary layer heights. The majority of MPLNET sites are located alongside NASA Aerosol Robotic Network (AERONET) sites.

ACTRIS (35 aerosol remote sensing facilities, 32 fixed and 3 mobile platforms) measures all four ACTRIS core RS variables using various types of multiwavelength high-power lidar. More details will be provided in subsequent chapters. ACTRIS also uses ceilometers and Doppler wind lidars at its cloud profiling observatories.

ARM has ceilometers and MPLs in each of its six observatories. Raman lidars are currently deployed at three observatories: the SGP, the Eastern North Atlantic (ENA), and the Bankhead National Forest (BNF). ARM also started operating HSRLs in 2010. These HSRLs are being upgraded with 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 at the SGP. A second system was deployed at the BNF observatory in 2025, which also includes an HSRL channel at 1064 nm. A new third system is being built for Alaska's North Slope (NSA). The Southern Great Plains (SGP) region is located in Lamont, Oklahoma, United States. The North Slope of Alaska (NSA) is centered in Utqiaġvik (formerly Barrow), Alaska, United States. The Eastern North Atlantic (ENA) is located on Graciosa Island in the Azores, Portugal. The Bankhead National Forest (BNF) is located in the southeast United States.

In following chapters, we present the recommendations for operation and calibration procedures for remote sensing instruments operated by the three networks ACTRIS, MPLNET, ARM, based on the conclusions of the *Deliverable D2.1 Identification of opportunities for harmonised calibration and operation practices and data production software*. This is available via the CARGO-ACT website at this link.

2.2 Context

A brief summary of the similarities and differences among the lidar networks under consideration are given in Table 3, where the green colour represents common features and red represents major differences, as identified in the CARGO-ACT D2.1 document.

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Table 4 Highlights of the commonalities and differences between the lidar networks: common features in green; major differences in red.

Aspect	ACTRIS (EU)	ARM (US)	MPLNET (US)
Primary Focus	Aerosol Remote Sensing in European observatories	Comprehensive atmospheric profiling, including aerosols, clouds, and boundary layers	Global Aerosol and cloud vertical profiling using Micro-Pulse Lidar systems
Key Instruments	High-power lidars (MWBL_BR_PL), photometers, ceilometers, Doppler lidars	Multiple lidar systems (MPLs, Raman, HSRLs, Doppler lidars)	Micro-Pulse Lidars (MPLs and miniMPLs), ancillary photometers
Instrument challenge	Diverse instrument designs make harmonization difficult.	Multi-instrument. Instrument-specific protocols tailored for each type.	Standardized lidar instruments (MPLs only) and ancillary photometers (AERONET) ensures uniformity but limits vertical profile capabilities.
Calibration Facilities	Centralised: High power lidars: CARS (instrument) and ARES (data) Doppler lidars: CCRES (instrument) and CLU (data)	Distributed: Vendor-specific and site-specific corrections for each instrument type.	Centralized calibration at NASA GSFC. Onsite calibration data sent to and processed at the central facility. Regional calibration centers under consideration.
Calibration methodology	Combines hardware characterization and software corrections for traceability. High power lidars: Overseen by CARS (instrument) and ARES (data) Doppler lidars: Overseen by CCRES (instrument) and CLU (data)	Focus on vendor and field-specific calibrations for consistency. QA/QC procedures embedded in data streams. Focused on robust, instrument-specific Automated and manual QA/QC integrated into daily operations.	Calibration analysis, QA/QC, and corrections performed centrally at GSFC. Calibration measurements performed routinely every 1-2 months.
Calibration procedures	Specific QA tests performed in defined conditions. Test data analysed by CARS (CCRES for DWL). Instrument related processing parameters (correction factors) used in the processing chain. Multiple quality checks on data products.	Instrument-specific calibration corrections, such as overlap and dead-time corrections, applied regularly.	Uniform calibration protocols for all MPLs; includes detector deadtime and darkcount, afterpulse (laser-detector crosstalk), overlap, and polarization.
Centralized Processing	**Single Calculus Chain (SCC)**: All lidar data from ACTRIS stations are processed using a centralized system.	Processing varies by instrument type, with tools developed by vendors and researchers. Data processed at	All data processing is centralized at NASA's GSFC, ensuring

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		the ARM Data Center and quality controlled by the data quality office and instrument mentors. Centralized system	consistency across the network.
Algorithm Consistency	SCC enforces uniform algorithms for data processing, reducing variability in outputs across observatories.	Each instrument type has specific algorithms, often tailored for site conditions or instrument modifications.	Uses standardized algorithms for all MPLs, applied during central processing.
Data Levels	Data are processed into quality-checked levels, with corrections applied for instrumental biases and atmospheric variability. **Level 1** (incomplete QA/QC) / **Level 2** (complete QA/QC)	ARM produces data at multiple levels (**raw, ingest, corrected, and final products**) using its ingest pipeline.	Products include: **Level** 1 and **Level 1.5 (both in NRT)**, and final **Level 2**. Post calibrations and QA/QC are applied to Level 2. Level 2 data are available weeks to months later (Level 2 aerosol products are dependent upon Level 2 AERONET data availability)
Instrument Installation	Requires co-located high-power lidar and photometer; strict environmental conditions.	Site-specific installation and maintenance protocols for each instrument.	Standardized enclosures for MPLs; environmental controls (e.g., temperature, humidity).
Data Collection	**Minimum of 5 lidar observations of several hours per week**; Detailed guidelines for duration and timing. **Fully autonomous operation** for DWL ceilometer and PollyXt Raman lidars	**Fully autonomous operation** for MPLs and ceilometers; preventative maintenance required.	**Automated** data are collected continuously (24/7) at all sites, automated data transmission and calibration updates; bi-monthly checks for key calibrations.
Maintenance	Regular QA tests for stability **each year & at change** (e.g., polarization calibration, zero bin tests).	**Daily and quarterly checks**, including afterpulse and dark count corrections.	Routine inspections and calibration updates **every 1-2 months**.

2.2.1 Standard Operating Procedure (sections 3.1.2.2 and 3.2.2.3 of D2.1)

Operation procedures are instrument and network specific. Harmonization is unlikely due to the use of different lidar instruments and data acquisition protocols by all three networks studied. In addition, there

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are a variety of station types among these networks, ranging from remote locations requiring automated processes, to large facilities with personnel teams operating the instruments. However, debates on best practices can be organized to identify common aspects, such as lidar inspection, laser warming, acceptable signal levels, regular maintenance, and so on.

2.2.2 Calibration Procedures (sections 3.1.2.1 and 3.2.2.1 of D2.1)

One significant distinction between ACTRIS versus ARM and MPLNET is the variety of lidar instruments supported by the protocols (calibration, operation, and data processing). ACTRIS employs non-standardized instruments, whereas ARM and MPLNET use standardized or similar design instruments. Therefore, it is not realistic to harmonize calibration procedures at an instrument level.

However, there are common types of calibration procedures utilized by the networks, some may not be applicable for all instruments:

- Detector calibration
- Laser Calibration
- Detector-Laser Crosstalk Calibration
- Optical Component Calibration
- Overlap Calibration
- Polarization Calibration

In this case, harmonization would be defined as specifying minimum goals for each calibration that are not instrument specific. In addition, identifying which lidar types and data products require each calibration to be applied. Examples include the following scenarios. Every lidar requires a detector calibration of some sort. Traditional lidars with separate transmitter and receiver may not require Detector-Laser crosstalk calibration, while lidar transceiver designs do. Overlap calibrations are only required if the data product is sensitive to overlap and data will be reported in the overlap region. For instance, volume depolarization ratio is not sensitive to overlap (in the idealized case) but such calibrations would be required in the overlap region for aerosol retrievals. Finally, an example of setting minimum goals could be to specify a depolarization ratio bias limit.

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2.2.3 Doppler wind lidar capabilities (section 3.2.2.1 of D2.1)

ACTRIS and ARM use similar commercial instruments and have developed successful procedures for calibration, QA/QC, and automated processing. There is an opportunity to collaborate on converging and extending the methods used.

2.3 Recommendations for common calibration and operation procedures

The analysis performed and documented in the CARGO-ACT D2.1 of the Aerosol, Clouds, and Trace Gas Research InfraStructure (ACTRIS), NASA Micro-Pulse Lidar Network (MPLNET), and Atmospheric Radiation Measurement Facility Unit (ARM) lidar networks served as the foundation for the discussion of the set of recommendations in the current document.

These three networks are designed to serve specific applications and scientific objectives. However, there are several common challenges that could be addressed in order to improve the consistency of aerosol lidar data product quality.

- ACTRIS can align with the technical requirements and design of the ARM HSRLs, including associated protocols, tools, and algorithms, to enhance its high spectral resolution capabilities.
- All three networks are actively considering the implementation of polarization channels and the necessary calibration procedures. ACTRIS has made significant progress in developing hardware and software solutions to help calibrate depolarization measurements, including specialized tests to determine the depolarization correction factor. MPLNET has developed a reliable polarization calibration and processing protocol that is tailored to its unique eye-safe transceiver design. Collaboration in this area could result in the creation of a comprehensive list of best practices for existing lidar systems. This framework should be sustained and expanded to accommodate new lidar technologies.
- Each lidar network has a unique design that cannot be easily modified due to the costs and expertise required. However, one calibration procedure used by all networks can be standardized: direct comparison with a reference lidar. This procedure can be defined by common criteria for evaluating the performance of the lidar and the tests that will be used.

In order to achieve an effective harmonization of calibration and operation procedures, a working group should be formed including members provided from each network. The working group would be tasked with development of harmonization definitions and standards, and responsible for maintaining and evolving them over time.

The working group would also be responsible for organizing direct intercomparisons among reference lidars from each network. The intercomparisons would provide the criteria for assessing the performances of the lidars and applied procedures, and refinement of the harmonization standards.

The outcome of this working group would be a set of achievable standards that accommodates instrument heterogeneity and network variety and focuses on higher level standards such as the common calibration types discussed above. Best practice SOP and calibration procedures for specific lidar and for network deployments can be created where feasible, for instance commercial lidars with existing standard configurations.

Funding is the primary obstacle for this objective. Dedicated intercomparisons and harmonization efforts between networks are not likely included in existing funding for all networks. We suggest this type of effort be included in future network budgets and work plans in future. This should be further explored during the implementation of the CARGO ACT.

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