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1. INTRODUCTION

This deliverable provides a report on the atmospheric boundary layer height (ABLH) measurement campaign planned to assess and optimize MIPA (Morphological Image Processing Approach) algorithm for the retrieval of ABLH from lidar data. MIPA has been recently developed in the framework of ACTRIS¹. In particular, the following actions are planned:

- MIPA assessment for both high-power lidar (HPL) and ceilometers (low-power lidar - LPL)
- unattended usage of MIPA on lidar observations made by all ACTRIS Italian stations.

The first task is necessary because only a partial assessment of MIPA has been performed up to now, where the ABLHs retrieved from temperature and pressure vertical profiles provided by high-resolution global numerical weather predictions (NWP) were used for comparative purposes. The comparisons show that, on average, among all the lidar algorithms considered for the retrieval of ABLH, MIPA was the one delivering the closest values to those of NWP, but the usage of a reliable reference is necessary. The lidar algorithms compared with MIPA rely on gradient detection techniques and the use of the wavelet covariance transform (WCT). The first one estimates the ABLH by finding the height where the aerosol concentration abruptly decreases (assuming that the aerosol particles within the ABL can be used as a proxy to study the boundary layer vertical structure and time variability). As elastic backscatter lidars measure vertical profiles proportional to the atmospheric aerosol concentration, ABLH can be estimated by looking at extremum of the derivative of such profiles (derivative method). The WCT method is based on a convolution of elastic backscattered lidar profiles with wave function (wavelet). Haar wavelet function are particularly useful to detect gradients as they implement a band-pass filter with cut-off frequencies depending on a wavelet parameter (dilation). Both these methods suffer from two main limitations: they are dependent by the absolute intensity of lidar profiles (and so they need to be tuned differently when applied to different sensors), and they operate on single lidar profiles (and so they cannot consider the correlation among close in time lidar profiles). MIPA overcomes both these limitations working on composite image representing continuous timeseries of vertical profiles of any variable proportional to the atmospheric aerosol content. Such variable can be for example total attenuated backscatter coefficient, particle backscatter or even elastic range corrected signal. MIPA first detects the edges of input image and, in a second step, the ABLH are determined by making an object-based analysis of these edges that uses specific mathematical morphology filters. The advantage of this approach is to be quite independent of the absolute values of the input image and to rely only on the correlations (in both time and in space) among close image datapoints. NWPs were used as the number of radiosoundings co-located with the considered lidar observations was limited, and not suitable for a dense enough reference grid. To fill this gap a measurement campaign will be organized at CIAO (CNR-IMAA Atmospheric Observatory), where a quite complete set of atmospheric sensors is operative, including HPLs, LPLs, Doppler lidar and radar systems, as well as manual and automatic radiosounding systems.

An intensive observation period is planned in the frame of ITINERIS Activity 4.15.1 in order to provide simultaneous measurements of ABLH with radio soundings and remote sensing techniques, available at CIAO. All the CIAO sensors relevant for the study of the ABLH will be operative 24/7 and at least 6 radiosoundings per day will be performed, adopting GRUAN (GCOS Reference Upper Air Network) procedures and algorithms. Such experimental set-up will ensure a quite dense reference and representative dataset for the characterization of ABLH using different techniques

¹ Vivone, G., D'Amico, G., Summa, D., Lolli, S., Amodeo, A., Bortoli, D., and Pappalardo, G.: **Atmospheric boundary layer height estimation from aerosol lidar: a new approach based on morphological image processing techniques**, *Atmos. Chem. Phys.*, 21, 4249–4265, <https://doi.org/10.5194/acp-21-4249-2021>, 2021

under distinct atmospheric conditions. Additionally, the measurement campaign will provide the opportunity to optimize MIPA for LPL as, up to now, the algorithm has been tested only for HPL.

The main goal of this measurement campaign is to provide a tool that will make available the extension of the unattended MIPA assessment to all ACTRIS Italian stations with an active aerosol remote sensing component, considering both the available HPL and LPL observations. With the achievement of this objective, ITINERIS will deliver homogenized ABLH in near real time for all ACTRIS Italian stations, coherent with the 100% digital outcome of the project.

Moreover, the measurement campaign dataset will be a valid testbed for the development of new algorithms to retrieve the ABLH like for example the ones based on machine learning approaches.

2. MEASUREMENT CAMPAIGN

The instruments participating to the CIAO Atmospheric Boundary Layer Height measurement campaign are reported in Tab. 1. The main goal is to have different types of remote sensing instruments operating simultaneously and continuously 24/7 together with a frequent radiosondes' launches to establish a reference dataset for the ABLH retrieval. As different ABLH retrievals are based on different assumptions, the quite large number of instruments participating in the campaign is expected to be an added value to assess the impact of these assumptions under different atmospheric conditions. ABLH retrievals from lidar measurements, for example, use the atmospheric aerosols as tracers of the ABL, which is supposed to be always well-mixed. This assumption may show some limitations when the aerosol content is particularly low or in case of low clouds and precipitation (when lidar measurements are not possible). Moreover, a particularly low ABLH (below the lidar full overlap height) is not detectable, independently of the retrieval algorithm. In addition, there are different conditions under which the ABL is formed (non-turbulent, cloud-driven, convective, wind shear, etc.) and, consequently, ABL retrieval from the lidar measurements should be assessed in each one of those. In this context, the use of sensors like Doppler lidar and radar can help in detecting the lidar limitations and can provide a useful ABL classification to be correlated with ABLH retrieval results.

Tab. 1: Instruments involved in the CIAO Atmospheric Boundary Layer Height measurement campaign.

<i>Sensor Type</i>	<i>Instrument</i>	<i>Main Products</i>
HPL	Fixed wavelength Lidar	Multi-Raman Aerosol backscatter @1064, 532 and 355nm Aerosol depolarization ratio @1064, 532 and 355nm
	Mobile wavelength Lidar	Multi-Raman Aerosol extinction @532 and 355nm
	MUSA	Aerosol backscatter @1064, 532 and 355nm Aerosol depolarization ratio @532nm Aerosol extinction @532 and 355nm
Doppler Radar	MIRA36 (35.5GHz)	Doppler spectrum Doppler velocity Linear Depolarization Ratio

	Halo Photonics Stream LineXR (1.5 μm)	Aerosol/cloud backscatter Particles' radial velocity Air masses vertical and horizontal velocity
LPL	CL51 (905nm)	Aerosol backscatter Cloud base height
	CL31 (905nm)	
	CHM15k (1064nm)	
Microwave Radiometer	RPG-HATPRO-G5	Temperature, humidity and cloud liquid water profiles Integrated Precipitable Water Vapour (IPWV) Cloud Liquid Water Path (LWP)
Radiosounding system	MW41 (manual)	Temperature, pressure and humidity profiles
	AS13 (automatic)	
In situ	Aethalometer AE33	Absorption coefficient and equivalent Black Carbon (eBC) concentration
	Nephelometer Aurora 3000	Scattering and back scattering coefficient
	Aerodynamic Particle Size APS 3321	Particle size distribution (0.5-20 μm)
	Condensation Particle Counter (CPC 3750)	Particle number concentration (>10 nm)
	Scanning Mobility Particle Sizer (SMPS 3938)	Size distribution and Concentration (10-800nm)
	ToF-ACSM	Chemical composition and mass concentration of non-refractory aerosol (<1 μm)
	PMx samplers	PM10, PM2.5, PM1 concentration

Besides remote sensing measurements there is the plan to have a very frequent scheduling of radiosoundings. The radiosonde launches frequency is a crucial factor for the assessment of the MIPA algorithm, as in this way there will be an appropriate reference dataset for the ABLH retrieval against which compare the ABLH retrieved by MIPA. CIAO is the ideal site for performing this kind of experiment, as it is equipped with two radiosounding systems (one of them automatic), that we plan to use at least 6 times per day adopting GRUAN procedures and algorithms. The exact scheduling of the radiosonde launches will be evaluated case by case. In general, we plan to have denser launches in correspondence of ABL transition periods or during special events like dust intrusions.

Aerosol in situ measurements will be continuously running during the campaign providing useful information about the aerosol full characterization at the ground at 1 minute time resolution. Such information will be of interest for Task 4.14 "Impact of atmospheric boundary layer height on aerosol and trace gases concentration at the ground". The aerosol ground-based remote sensing and in-situ measurements collected during the ABLH campaign will be also important for the activities of Task

4.11 “Aerosol typing” and 4.12 “Aerosol source identification”². Data collected during the campaign will be published with DOI and will be made available through the ITINERIS Hub and datasets. Data will also be part of the international “homeless data portal” in the frame of the European atmospheric Research Infrastructure data center (EBAS).

In the following sections, the technical specifications of the main instruments involved in the campaign are reported.

2.1 Multi-wavelength Raman Lidars

Three different multi-wavelength Raman lidars are operating at CIAO. Such lidars are fully compliant with ACTRIS requirements and have been validated by the lidar calibration center of ACTRIS (CARS).

2.1.1 Fixed Multi-wavelength Raman Lidar

The fixed multi-wavelength Raman lidar system has been designed to provide multi-wavelength elastic (1064, 532 and 355 nm), Raman (607, 407 and 387 nm) and depolarization (1064, 532 and 355 nm) measurements for the retrieval of optical and microphysical properties of the atmospheric particles and water vapor mixing ratio profiles. The system was installed in 2021 and it is in the optimization phase.

The system is in biaxial configuration and is based on two Nd:YAG laser sources: one emitting radiation at 532 and 355 nm, with 10Hz repetition rate, the other emitting radiation only at 1064 nm, with 20 Hz repetition rate, to avoid polarization purity loss due to the SHG and THG crystals.

Two Cassegrain telescopes (with diameters of 400mm and 200mm) collect the backscattered radiation from the atmosphere to cover an altitude range from 200m (minimum full overlap altitude) up to at least 30km.

For each telescope, optical channels are available at 1064, 532, 355 nm (parallel and perpendicular polarization components for the three wavelengths), 607, 387, and 407 nm for a total of 18 channels.

CCD cameras for UV and IR are mounted on both telescopes to monitor the alignment of laser beams sent into the atmosphere. The polarization calibrators are based on the $\pm 45^\circ$ technique.

Detection is performed with an APDs at 1064 nm and by photomultipliers for all the other wavelengths. Acquisition is performed in analog mode at 1064 nm and in analog and photoncounting modes for the other wavelengths. The vertical resolution of the raw profiles is 3.75m. In the analog mode, the standard deviations of the signals are also acquired up to 10km, for the error calculation. Laser radiation measurements through photodiodes are also acquired to monitor the laser energy stability.

The system is fully motorized for laser beams alignment, telecover test, dark current measurements and polarization calibration. Moreover, it is fully automatized, allowing measurements and tests to run in an unmanned and programmed way.

The system is hosted in a 20ft container, with internal RH and T fully under control, and has been designed to operate 24h/7d. It is also equipped with an external meteorological station.

The lidar system, that is part of EARLINET, is one of the instruments of the Potenza ACTRIS national facility and is also one of the reference instruments of the ACTRIS Central Facility CARS (Centre for Aerosol Remote Sensing) and provides the systematic lidar measurements scheduled in ACTRIS/EARLINET activities.

² *Mona L.* (2023). **Atmosphere WP implementation plan**. PNRR – ITINERIS project deliverable, February 2023 (Public).

2.1.2 Mobile Multi-wavelength Raman Lidar

The mobile multi-wavelength Raman lidar system has been designed to provide multi-wavelength elastic (1064, 532 and 355 nm), Raman (607 and 387 nm) and depolarization (1064, 532 and 355 nm) measurements for the retrieval of optical and microphysical properties of the atmospheric particles. The system was installed in 2021 and is in the optimization phase.

The system is in coaxial configuration (but can also operate in biaxial configuration) and is based on two Nd:YAG laser sources operating at 20 Hz: one emitting radiation at 532 and 355 nm, the other emitting radiation only at 1064 nm, to avoid polarization purity loss due to the SHG and THG crystals.

One Cassegrain telescope, with diameter of 300mm, collects the backscattered radiation from the atmosphere to cover an altitude range from 200m (minimum full overlap altitude) up to at least 20km.

Optical channels are available at 1064, 532, 355 nm (parallel and perpendicular polarization components for the three wavelengths), 607 and 387 nm for a total of 8 channels.

CCD cameras for UV and IR are mounted to monitor the alignment of laser beams sent into the atmosphere. The polarization calibrators are based on the $\pm 45^\circ$ technique and are operated in manual mode.

Detection is performed by means of APD at 1064 nm and by photomultipliers for all the other wavelengths. Acquisition is performed in analog mode at 1064 nm and in simultaneous analog and photoncounting modes for the other wavelengths. The vertical resolution of the raw profiles is 3.75m. In the analog mode, the standard deviations of the signals are also acquired up to 10km, for the error calculation. Laser radiation measurements through photodiodes are also acquired in order to monitor the laser energy stability.

The system is motorized for laser beams alignment, telecover test, dark current measurements. Moreover, it is completely automatized, allowing to perform in a programmed way measurements and tests. It can be operated and controlled remotely and is able to run measurements and tests in an unmanned and programmed way.

The system is compact and hosted in a small container, with RH and T internal monitoring and setting. It is also equipped with meteo station and with a radar to check the presence of aircrafts close to airports.

The lidar system is one of the instruments of the Potenza ACTRIS national facility and is also one of the reference instruments of the ACTRIS Central Facility CARS (Centre for Aerosol Remote Sensing). It can be used in field campaigns and is used in intercomparison campaigns planned in CARS activities.

2.1.3 MUSA

MUSA (Multiwavelength System for Aerosol) is a mobile multi-wavelength lidar system based on a Nd:YAG laser equipped with second and third harmonic generators and on a Cassegrain telescope with a primary mirror of 300mm diameter.

The three laser beams at 1064, 532 and 355nm are simultaneously and coaxially transmitted into the atmosphere in biaxial configuration. The receiving system has 3 channels for the detection of the radiation elastically backscattered from the atmosphere and 2 channels for the detection of the Raman radiation backscattered by the atmospheric N₂ molecules at 607 and 387 nm. The elastic channel at 532 nm is split into parallel and perpendicular polarization components by means of a polarizer beamsplitter cube. The backscattered radiation is acquired at 1064 nm in analog mode and at the other wavelengths both in analog and photon counting mode. The calibration of depolarization channels is made automatically using the ± 45 method. The typical vertical resolution of the raw profiles is 3.75m with a temporal resolution of 1 min.

The system is compact and transportable. It was developed in 2009 in cooperation with the Meteorological Institute of the Ludwig-Maximilians-Universität of Munich and it is one of the reference systems used in the frame of the EARLINET Quality Assurance programme.

The system was involved in seven intercomparison measurement campaigns within the FP6 project EARLINET-ASOS: EARLI09 (EARLINET Lidar Intercomparison, held in Leipzig-Germany in May 2009, involving 11 lidar systems) and SPALI10 (SPAIN Lidar Intercomparison, held in Madrid-Spain in 2010); and within the ACTRIS FP6 and ACTRIS-2 H2020 projects: NALI13 (NAPOLI Lidar Intercomparison, held in Napoli-Italy in 2013), LELI13 (LECCE Lidar Intercomparison, held in Lecce-Italy in 2013), ATHLI16 (ATHENS Lidar Intercomparison, held in Athens-Greece in 2016), ISPLI18 (ISPRa Intercomparison, held at JRC in Ispra-Italy in 2018), THELI18 (THESSALONIKI Lidar Intercomparison, held in Thessaloniki-Greece in 2018).

2.2 Doppler Radar

2.2.1 MIRA36

A cloud radar MIRA36 designed by METEK GmbH has been operating at CIAO since March 2009. In 2022 the radar was upgraded to a MIRA35. It is a mono-static pulsed Ka-Band Doppler radar for unattended long-term observation of clouds properties. In the configuration operative at CIAO, linear polarized pulses are transmitted in the atmosphere, while co- and cross polarized backscattered signals are received simultaneously to detect the profiles of the Doppler spectrum and related moments, such as the reflectivity factor and Linear Depolarization Ratio (LDR). The reflectivity is used to determine the density of cloud particles, while LDR helps to identify hydrometeors' shape and type.

The radar has a 1 m diameter antenna emitting microwave pulses at 35.5 GHz, with a peak power of 30 kW, duration of 200 ns and repetition rate of 5 KHz. The antenna beam width is $0.6^\circ \times 0.6^\circ$, the antenna gain is 49 dBi, while the radar sensitivity is -44 dBZ (-53 dBZ) at 5 km 0.1 sec (10 sec) time resolution. The Doppler velocity resolution is better than 0.05 m/s. The LDR accuracy is within +/- 2.0 dB, while the receiver calibration accuracy is within +/- 1 dB.

A clutter fence around the antenna strongly suppresses the ground clutter echo. The radar is also equipped with a 3D scanning unit and it has been the first Ka-band radar in Europe able to perform a 3D scanning of the atmosphere in order to derive wind speeds and hydrometeors' size distribution and shape.

Radar profiles typically measured at CIAO have a vertical resolution of 30 m and a temporal resolution of 10 seconds. The typical measurement range is from 100 m to about 15 km, but during scanning scenarios the maximum range can be extended along the off-zenith line-of-sight.

2.2.2 Halo Photonics Stream LineXR

The Doppler lidar emits laser light pulses at 1.5 μm , with low energy ($\sim 100 \mu\text{J}$) and high repetition frequency (10kHz). It provides range-resolved measurements of backscattered radiation from atmospheric aerosol/cloud particles and particles' radial velocity (i.e. the velocity component parallel to the laser beam), based on the Doppler shift of the backscattered radiation. Exploiting the lidar full upper hemispherical scanning capability, air masses vertical and horizontal velocity (i.e. wind vertical and horizontal components) can be estimated through the troposphere, using aerosol particles and/or cloud hydrometeors as tracers. Range and time resolutions of the products provided are user-selectable, with minimum values in the order of 30 m and 1 s, respectively.

2.3 Ceilometers

2.3.1 CL51

The ceilometer Vaisala CL51, in operation at CIAO since December 2022, employs an eye-safe diode laser transmitter, emitting short light pulses at 905 nm in zenith or near zenith direction using a single-lens trans-receiver. The light backscattered from atmospheric particles (e.g.: aerosols, clouds, fog and precipitation) is received to detect the attenuated backscatter profiles used for unattended and continuous characterization of aerosol and cloud layering through the troposphere, as well as for the detection of fog and precipitation. The ceilometer profiles have high vertical and temporal resolution, typically in the order of 10 m and 10 s, and a typical measurement range for clouds from 15 m to 12 km above the ground.

2.3.2 CL31

The ceilometer Vaisala CL31, in operation at CIAO since December 2022, employs an eye-safe diode laser transmitter, emitting short light pulses at 905 nm in zenith or near zenith direction using a single-lens trans-receiver. The light backscattered from atmospheric particles (e.g.: aerosols, clouds, fog and precipitation) is received to detect the attenuated backscatter profiles used for unattended and continuous characterization of aerosol and cloud layering through the troposphere, as well as for the detection of fog and precipitation. The ceilometer profiles have high vertical and temporal resolution, typically in the order of 10 m and 10 s, and a typical measurement range for clouds from 15 m to about 8 km above the ground.

2.3.3 CHM 15k

The ceilometer Lufft CHM 15k, in operation at CIAO since September 2023, employs an eye-safe diode-pumped Nd:YAG laser transmitter, emitting short light pulses at 1064 nm in zenith or near zenith direction, using a biaxial dual-lens trans-receiver. The light backscattered from atmospheric particles (e.g.: aerosols, clouds, fog and precipitation) is received to detect the attenuated backscatter profiles used for unattended and continuous characterization of aerosol and cloud layering through the troposphere, as well as for the detection of fog and precipitation. The ceilometer profiles have high vertical and temporal resolution, typically less than 10 m and 15 s, and a typical measurement range for clouds from 10 m to about 15 km above the ground.

2.4. Microwave Radiometer

The ground-based microwave radiometer RPG-HATPRO-G5, designed by Radiometer Physics GmbH (RPG), has been operating at CIAO since December 2022 and replaced the old microwave profiler MP3014 (designed by Radiometrics Corporation) not operational anymore. It measures the sky brightness temperature (Tb) at 14 frequencies: 7 in the K-band, distributed from the centre onto the wing of the 22 GHz water vapour resonance absorption line, the rest are in the V-band, distributed on one shoulder of the 60 GHz oxygen spin-rotation band. The radiometer is equipped with a scanning infrared radiometer, able to measure cloud base brightness temperature (Tb) within the spectral range of 9.6 to 11.5 μm , and with an automatic weather station for measuring surface temperature, humidity, pressure, rain rate and wind (speed and direction). A mitigation system consisting of a blower, a heater and the hydrophobic coating of radome minimize errors resulting from the accumulation of precipitations and dew on the radiometer's radome. The radiometer is also equipped with an azimuth positioner for full sky scanning.

Temperature, humidity and cloud liquid water profiles up to 10 km above the ground (level 2 products) are retrieved from Tb at K and V-band frequencies, using a neural network algorithm trained by forward modelling several years of historical radiosonde dataset. The above profiles have

vertical resolution that increases with the altitude range with values less than 100 m up to 2.5 km, between 120 and 200 m up to 6 km and 300 m above. Finally, the inversion algorithm provides also an estimation of the Integrated Precipitable Water Vapour (IPWV) and the cloud Liquid Water Path (LWP).

2.5. Radiosounding Systems

Balloon-based measurements of temperature, pressure, humidity and wind (speed and direction) through the troposphere and stratosphere are performed at CIAO using three different VAISALA MW41 radiosounding systems, two manual (fixed and mobile) and one equipped with an automatic launcher (VAISALA autsonde system AS13). The latter is able to perform up to 24 radiosoundings automatically or remotely controlled. Moreover, the system can also be scheduled for activating up to two spare radiosoundings in order to prevent any faults in the launch procedure. All MW41 systems are also able to manage the data received from the ozonesonde digital interface for measurements of the ozone mixing ratio atmospheric profile.

Since 2010, CIAO is a site of the Global Climate Observing System (GCOS) Reference Upper-Air Network (GRUAN, www.gruan.org), providing long-term high-quality measurements of atmospheric essential climate variables (ECVs) from the surface, through the troposphere, and into the stratosphere. These measurements are appropriate for studying atmospheric processes, identify pollution transports, detection and analysis of trends, as well as for calibration and validation of measurements and retrieval algorithms from other ground-based and satellite observing systems or networks (for example, radiosoundings measurements are often used to calibrate ground-based Raman lidars for the retrieval of atmospheric temperature and humidity profiles).

2.6 In situ measurements

The instrumentations for aerosol in-situ analysis will be able to provide real-time (online) and continuously measurements, while the filters collected by the PM samplers used for the continuous sampling of PM₁₀, PM_{2.5} and PM₁ will be subjected to further chemical analysis with different offline instruments.

2.6.1 Aethalometer (AE33, Magee Scientific)

The Aethalometer AE33-Dual Spot, operating at seven different wavelengths in the range 370-950 nm, is used for the real-time detecting of particulate which absorbs light, known as Black Carbon (BC), formed during the incomplete combustion of carbonaceous matter from biomass burning and fossil fuel. The principle of the aethalometer is to measure at given time intervals the attenuation of a light beam transmitted through a filter where the particulate is continuously collected, the rate of change of optical transmission combined with the air flow rate monitored through a mass flowmeter allows to determine the absorption coefficient, then converted into equivalent black carbon (eBC) concentration by means of the mass-absorption cross section (MAC, using the user manual default values for each wavelength). Increases in optical absorption at shorter wavelengths may be interpreted in terms of the presence of so-called brown carbonaceous material, usually an indicator of emissions from biomass combustion or dust. This wavelength dependency allows to separate the potential contribution from fossil fuel/traffic from the solid fuels/biomass burning sources. The Aethalometer is connected to the PM₁₀ common inlet (shared with the Aerodynamic Particle Sizer and Nephelometer) and is equipped with a sample stream dryer (Magee Scientific) exploiting a semi-permeable Nafion membrane which keeps the RH well below 40% since, besides the possible instrument damage caused by water condensation, the interaction of water with aerosol species is

well known to change its physical and optical properties, thus leading to inaccuracies in the determination of BC content.

2.6.2 Integrating Nephelometer (Aurora 3000, Ecotech)

The Multi Wavelength Integrating Nephelometer is used to measure the total scattering σ_{sp} and the backscattering σ_{bsp} coefficients (integrating within the angular range 9° - 170° and 90° - 170° , respectively), both correlated to the particle concentration. The peculiarity of the instrument is the utilisation of a light source emitting at three distinct wavelengths: the light at 635 nm (red) interacts strongly with large particulate matter such as pollen, dust, sea salt; the light at 525 nm (green) interacts strongly throughout the human range of visibility (smog, fog, haze); the light source at 450 nm (blue) interacts strongly with fine particles, such as wood fires and exhaust emissions. The Nephelometer is connected to the PM10 common inlet (shared with the Aerodynamic Particle Sizer and Aethalometer) and is equipped with a 36 inch long PermaPure Nafion MD-700 membrane which keeps the RH well below 40%, in order to prevent condensation of water droplets over the particles, which would increase their size and significantly change their scattering characteristics.

2.6.3 Aerodynamic Particle Sizer (APS 3321, TSI)

The APS spectrometer provides high-resolution real-time aerodynamic particle size distribution for the coarse fraction of the particulate. The optical size range of the APS is from 0.37 to 20 μm , but since the counting efficiency of APS below 0.8 μm aerodynamic diameter rapidly decreases and is unstable, it is advisable to consider only data from the particle number size distribution greater than 0.8 μm , as reported by “*ACTRIS Standard Procedures for In-Situ Aerosol Sampling, Measurements, and Analyses at ACTRIS Observatories*” (<https://www.actris-ecac.eu/actris-gaw-recommendation-documents.html>). In addition, since the spectrometer is connected to a PM10 common inlet (shared with the Nephelometer and Aethalometer), only data from the particle number size distribution lower than 10 μm should be considered.

The APS is based on the time-of-flight particle sizing, in which the aerodynamic size of a particle determines its rate of acceleration, with larger particles accelerating less than smaller ones due to increased inertia; the time of flight between two laser beams is recorded and converted to aerodynamic diameter using a calibration curve. The instrument is also able to measure in addition the light scattering intensity of the sized particles in the equivalent optical size range from 0.8 to 10 μm , thus providing further insights into the aerosol nature and composition. The APS is equipped with a 12 inch PermaPure Nafion membrane which keeps the RH well below 40%, in order to prevent condensation of water droplets over the particles, which would increase their size.

2.6.4 Condensation Particle Counter (CPC 3750, TSI)

The CPC is used to measure the number concentration of aerosol particles with a diameter larger than 10 nm. In the CPC, an aerosol sample is continuously drawn through a heated saturator where the butanol is vaporized and diffused into the sample stream. Then, the aerosol sample and *n*-butanol vapour pass into a cooled condenser where the *n*-butanol vapour becomes supersaturated and condenses on the particle surface causing them to grow. Particles are then counted individually as they pass through a laser-based optical detector. The CPC is connected to the PM2.5 common inlet (shared with the Scanning Mobility Particle Sizer and ToF-Aerosol Chemical Speciation Monitor) and is equipped with a 24 inch PermaPure Nafion membrane which keeps the RH well below 40%,

in order to prevent condensation of water droplets over the particles, which would increase their size (this Nafion is also connected to a Scanning Mobility Particle Sizer).

2.6.5 Scanning Mobility Particle Sizer (SMPS 3938, TSI)

The SMPS being able to provide the size distribution and concentration of the fine fraction of the particulate in the size range 10 nm – 800 nm. It consists of four components in sequence: 1) a pre-impactor which removes particles larger than the fixed upper limit of size; 2) a bipolar diffusion charger (model 3082, TSI) which confers a characteristic stationary charge distribution to the polydisperse particles by using a radioactive source (Kr-85); 3) a differential mobility analyzer column (DMA, model 3083, TSI) which separates the particles according to their electrical mobility by varying continuously the applied voltage within the column, 4) a condensation particle counter (CPC, model 3750, TSI) where the classified monodisperse particles are counted after condensation of *n*-butanol on their surface. The SMPS is connected to the PM2.5 common inlet (shared with the CPC and ToF-Aerosol Chemical Speciation Monitor) and is equipped with a 24 inch PermaPure Nafion membrane which keeps the RH well below 40%, in order to prevent condensation of water droplets over the particles, which would increase their size (this Nafion is also connected to a CPC). Moreover, a dry sheath air is needed for the SMPS to ensure particle sizing inside the DMA with a minimum fluctuation in RH and for this purpose a Silica Dryer Tube (model 3082, TSI) is incorporated in the DMA sheath flow system, which is a closed clean and dry loop.

2.6.6 Time-of-Flight Aerosol Chemical Speciation Monitor (ToF-ACSM, Aerodyne Research)

The ToF-ACSM spectrometer measures the mass concentration of chemical components of non-refractory submicron aerosol particles – i.e., organic substances, nitrates, sulphates, ammonium, and chloride – thus generating an invaluable database for the modelling community to characterise the particulate sources apportionment and evolution. The operational principle of the instrument is the following: the aerosol enters the inlet where the aerodynamic lens efficiently samples and focuses submicron particles to the subsequent vacuum chamber; here, the particles impact on a resistively heated porous tungsten surface at approximately 600 °C which vaporises the non-refractory particulate; the vaporised matter is subsequently ionised by electronic impact and detected through the ToF analyzer. The ToF-ACSM is connected to the PM2.5 common inlet (shared with the CPC and SMPS) and is equipped with a 24 inch Nafion membrane which keeps the RH well below 40%, in order to eliminate the complicating inlet effects due to particle composition dependent water uptake.

2.6.7 PMx samplers (SWAM 5a-Dual Channel Monitors, FAI Instruments)

The two PMx samplers are used for the continuous sampling and measurement of PM10, PM2.5 and PM1 mass fractions collected over 24h on both Teflon and quartz filters; the determination of the mass of collected samples is based on the *beta*-ray attenuation monitoring. Each PMx sampler is equipped with two independent sampling lines (i.e., PM10/PM2.5 and PM2.5/PM1), thus enabling the simultaneous collection of different PM fractions on independent filters.

The filters collected during the campaign will be subjected to further analysis with different offline instruments such as the Scanning Electron Microscope (SEM), the Inductively Coupled Plasma – Optical Emission Spectroscopy (ICP-OES) and the OC/EC analyzer.

The SEM will be used to examine the morphology of particles that, includes shape, size, and structure information, the ICP-OES will be used to determine the qualitative and quantitative elemental composition of the metals present in the atmospheric particulate and The OC/EC analyzer will be used to quantify the total carbonaceous content of the particulate matter (total carbon, TC) and the subfractions OC (organic carbon) and EC (elemental carbon).

3. CAMPAIGN PLAN

The ABLH measurement campaign was initially planned for the period October-November 2023. However, due to interrupted supply chains because of the volatile international landscape, the procurement and delivery of helium for the radiosonde launches could not be guaranteed for the abovementioned period. Unfortunately, the helium available quantity in CIAO was not sufficient to carry out the campaign, but the stored quantities was primarily used for the GRUAN mandatory routine activities. The helium shortage at the time of writing is overcome, it was nonetheless decided to further move the campaign away from winter months due to the adverse weather conditions that could affect the lidar measurements. Therefore, ***it was decided to move the activity to spring (March-June 2024)*** and take advantage of the fair weather and the possibility to encounter more diverse aerosol loads and origin conditions. In addition, the postponing of the campaign will benefit of the further measurement capabilities respect to the original plan of Autumn 2023, like the aerosol in situ component and the starting of automatic processing of the cloud remote sensing part.