



Atmospheric Boundary Layer Height from Commercial Ceilometers: Optimization and Validation of the MIPA Algorithm

Antonio Mazza¹, Benedetto De Rosa¹, Ilaria Gandolfi¹, Emilio Lapenna¹, Simone Lolli¹, Fabrizio Marra¹, Lucia Mona¹, Ermann Ripepi¹, Marco Rosoldi¹, Gemine Vivone^{1,2}, and Giuseppe D'Amico¹

¹National Research Council of Italy, Institute of Integrated Methodologies for Earth Observation (CNR-IMIOT), Tito (PZ), Italy

²National Biodiversity Future Center, NBFC, Palermo, Italy

Correspondence: Antonio Mazza

Abstract. This study investigates the applicability of the Morphological Image Processing Approach (MIPA) for estimating the Atmospheric Boundary Layer Height (ABLH) from ceilometer observations. Based on our previous work, in which MIPA was assessed and validated using High Power LiDAR observations, the present study extends its application for the first time to three commercial ceilometers (CHM15k, CL31, and CL51). The analysis is based on a measurement campaign conducted at the CIAO (CNR-IMIOT Atmospheric Observatory) during spring 2024. Three case studies covering different atmospheric conditions were selected to quantify the retrieval performance. A grid search was performed to optimize MIPA for each ceilometer, while the retrieved ABLH values were evaluated against a reference dataset obtained from temporally frequent radiosonde launches. The retrievals were also compared with the proprietary algorithms implemented by the instrument manufacturers. Results demonstrate that MIPA provides robust ABLH estimates for the considered ceilometers and generally outperforms the corresponding operational retrievals. The optimization showed that only a limited subset of processing parameters required instrument-specific tuning, confirming the robustness of the proposed methodology. Among the investigated instruments, the CHM15k achieved the best overall performance, yielding the lowest RMSE and standard error with respect to radiosonde-derived ABLH. These results highlight the influence of sensor characteristics, such as signal-to-noise ratio and near-range measurement quality, on retrieval accuracy. Widespread availability, low cost, and continuous operation, together with MIPA's low computational cost, make ceilometers an attractive complement to advanced LiDAR systems, enabling denser and more continuous near-real-time ABLH monitoring networks at regional and potentially continental scales.

1 Introduction

The atmospheric boundary layer height (ABLH) is a crucial parameter to fully understand and characterize the lower part of the troposphere. In particular, the ABLH exhibits diurnal variability depending on the solar cycle (Mahrt, 1999) and has a significant impact on many important aspects such as the regulation of turbulence, convection, precipitation, heat exchange between Earth's surface and atmosphere, momentum, pollutants, and moisture (Mahrt, 1999; Su et al., 2020). Additionally, ABLH is also crucial for air quality, as it determines the available volume that anthropogenic pollutants emitted on the surface



can occupy. Especially during night conditions, the ABLH is typically below a few hundreds of meters above the surface and, consequently, the concentration of pollutants trapped below can be quite high, strongly degrading air quality (Kotthaus et al., 2023; Haeffelin et al., 2012). Consequently, accurate and dense ABLH measurements are fundamental in the resolution of air-quality-related issues, especially in a highly populated metropolitan area. Unfortunately, the spatial and temporal coverage of available observations is often insufficient to robustly characterize the variability of ABLH. Radiosonde soundings conducted worldwide within the World Meteorological Organization (WMO) global network have traditionally provided the reference measurements for monitoring ABLH evolution. However, these observations are unevenly distributed and their sampling frequency is often too low to resolve the diurnal cycle (typically limited to two launches per day) (Cimini et al., 2020). During recent decades, remote sensing techniques have proven to be a very useful tool to fill these observational gaps, as they can provide continuous measurements of ABLH at high resolution in both time and space (Haeffelin et al., 2012; Wiegner et al., 2014). The main idea behind this approach is to use the vertically resolved profiles of thermodynamic atmospheric variables measured by remote sensing techniques as a proxy of atmospheric boundary layer dynamics. Depending on the remote sensor capabilities, the physical quantity acting as proxy can be temperature, humidity, wind fields, and attenuated backscatter from clouds and aerosols. Consequently, instruments such as microwave radiometers, sodars, ceilometers, and LiDARs can be used to monitor ABLH 24/7 (Kotthaus et al., 2023; Haeffelin et al., 2012). However, it is important to remark that the ABLH derived from aerosol tracers can sometimes decouple from the true thermodynamic boundary layer, particularly during transition periods such as the evening collapse or morning growth, leading to potential discrepancies when comparing aerosol-based retrievals with temperature-derived radiosonde reference values. In particular, LiDARs and ceilometers are considered quite promising tools, as they can easily deliver continuous and high resolution timeseries of attenuated aerosol backscatter profiles, which, being proportional to atmospheric aerosol content, can be used to retrieve the ABLH. Consequently, the scientific community has made many efforts to develop automatic ABLH retrieval algorithms applied to LiDAR and ceilometer observations. Several methods are documented in the literature that range from simple and traditional approaches based on the detection of gradients in the first or second derivative of range-corrected elastic backscattered LiDAR signals (Flamant et al., 1997; Menut et al., 1999; Sicard et al., 2006; Summa et al., 2013) to more complex and advanced algorithms that apply the wavelet covariance transform (WCT) to the LiDAR signal (Compton et al., 2013; Morille et al., 2007; Baars et al., 2008; Dang et al., 2019). In this context, the Morphological Image Processing Approach (MIPA) (Vivone et al., 2021) has been developed and optimized (D'Amico et al., 2025) to retrieve accurate ABLH from LiDAR deployed in the framework of the EARLINET and the Aerosol, Clouds and Trace Gases Research Infrastructure (ACTRIS) (Pappalardo et al., 2014) and the non-EARLINET LiDAR system (Summa et al., 2023).

One of the main strengths of MIPA is the use of a fully image-based (2D) approach. Unlike the other available algorithms working on a single LiDAR profile, high resolution timeseries of LiDAR observations are analyzed as a single object (image). Due to this aspect, MIPA generally performs better than other traditional algorithms (Vivone et al., 2021; Summa et al., 2023; D'Amico et al., 2025), as it relies on both time and space correlations of the input data, and, moreover, it is relatively insensitive to the absolute intensity of the input LiDAR signals. The previous study presented in D'Amico et al. (2025) focused on the assessment and validation of MIPA using High Power LiDAR observations. Following that work, the present study investigates



the transferability of the same core processing framework to commercial ceilometer observations, characterized by different instrumental and signal properties. Thus, while the MIPA methodology builds upon the previously developed framework, its application to ceilometers and the instrument-specific optimization of its processing parameters represent the main novel elements of the present study. To investigate this possibility, a dedicated measurement campaign was organized at the CNR-IMIOT Atmospheric Observatory (CIAO) (Madonna et al., 2011; Laurita et al., 2025; De Rosa et al., 2025; Lapenna et al., 2025) where several active and passive remote sensing instruments capable of characterizing the atmospheric boundary layer have been continuously operating. In addition to such remote sensing equipment, the observatory is also equipped with two different radiosounding systems, particularly relevant to establish a robust ABLH reference dataset based solely on co-located (in both time and space) radiosoundings. In this study, we assess for the first time the applicability and the performance of MIPA across three different CIAO ceilometers (CHM15k, CL31 and CL51) operational during the campaign. To ensure a fair comparison among the instruments, a systematic grid-search optimization was performed independently for each ceilometer to identify the most suitable MIPA configuration. The retrieval performance was then evaluated against the radiosonde reference dataset. This allows us not only to evaluate the retrieval accuracy, but also to assess the robustness and transferability of the algorithm across different ceilometer architectures. The study is particularly relevant because, although ceilometers have a significantly lower signal-to-noise ratio (SNR) than LiDARs, they offer several characteristics that are particularly advantageous for ABLH monitoring. They are much cheaper devices than advanced LiDARs and consequently, ceilometer networks (such as, for example, E-PROFILE (Haeferle, 2020)) are more widespread and dense than the corresponding LiDAR networks. Moreover, in general, ceilometers run unattended under any atmospheric condition and are quite easy to operate even for unskilled personnel. Depending on their optical design (mainly due to the smaller size of the telescope they are equipped with), some ceilometers may provide vertical profiles characterized by a lower overlap with respect to advanced High Power LiDAR which are typically optimized for measurements extending into the free troposphere and above. The remainder of the manuscript is organized as follows. Section 2 reviews the definition of a ceilometer and the retrievable atmospheric aerosol parameters. Section 3 describes the measurement campaign from which the datasets used in this study were collected. Section 4 provides a brief overview of the MIPA algorithm, while Section 5 describes the experimental setup, including details on the instruments, datasets, and the measurement campaign. Section 6 presents the retrieval results, along with an analysis of the estimated ABLH in relation to the SNR. Finally, Sect. 7, summarizes the main findings and outlines the conclusions.

2 Ceilometers: definition and retrievable quantities

In this study, we adopt the definition of a ceilometer as presented by Wiegner et al. (2014): a single-wavelength backscatter LiDAR operating in the near-infrared region between 900 and 1100 nm to minimize strong Rayleigh scattering, with a pulse repetition frequency (PRF) typically in the low kHz range, and pulse energy low enough to ensure eye-safe operation. Ceilometers require minimal operational and maintenance costs, are easy to operate, and provide near-real-time data. In contrast, advanced LiDAR systems, while offering higher radiometric accuracy, are costly to acquire, operate, and maintain. As a result, they are sparsely distributed and restricted to a relatively small number of dedicated stations, leading to significant



gaps in spatial coverage and continuous data availability. The widespread deployment of ceilometers presents a valuable opportunity to fill these observational gaps, ensuring a more continuous and extensive flow of atmospheric information. Together, these points highlight the complementary role that ceilometers can play alongside advanced LiDAR systems in atmospheric monitoring, enabling denser networks with reduced operational expenses.

95 Ceilometers measure elastic backscatter profiles from which aerosol optical properties, primarily the particle backscatter coefficient, can be retrieved through inversion techniques that require instrument calibration, as demonstrated in Wiegner et al. (2014). However, the ABLH, i.e., the parameter of interest in this study, can be reliably estimated directly from raw backscatter profiles without calibration, making ceilometers particularly suitable for continuous boundary layer monitoring. In this work, three ceilometer models are investigated: the CHM15k manufactured by Lufft and the Vaisala CL31 and CL51
100 both manufactured by Vaisala. Their main technical specifications are summarized in Table 2. Although these instruments differ in design and performance, they provide vertical profiles of attenuated backscatter with high temporal resolution. The CL31 and CL51 are mono-axial systems, where the transmitter and receiver share the same optical axis. This configuration simplifies geometric alignment, reduces parallax errors, and ensures better overlap between the laser beam and receiver field of view (RFOV) at close ranges. However, it usually results in a narrower field of view. In contrast, the CHM15k employs a
105 biaxial design, with physically separated transmitter and receiver. This arrangement offers greater flexibility to reduce stray light effects and improve measurements at higher altitudes but requires a more complex electro-optical system and careful calibration to correct parallax and overlap effects.

According to the LiDAR equation, the backscattered power $P(\lambda, z)$ received at wavelength λ from height z is:

$$\begin{aligned} P(\lambda, z) &= \frac{K}{z^2} \cdot \beta(\lambda, z) \cdot T(\lambda, z) + P_{bkg}(\lambda) \\ &= \frac{K}{z^2} \cdot [\beta_m(\lambda, z) + \beta_p(\lambda, z)] \cdot T_m(\lambda, z) \cdot T_p(\lambda, z) + P_{bkg}(\lambda) \end{aligned} \quad (1)$$

110 where:

- K : calibration constant, comprising all system parameters that influence the detected backscattered signal.
- $\beta(\lambda, z)$: backscatter coefficient.
- $T(\lambda, z)$: atmospheric transmissivity.
- $P_{bkg}(\lambda)$: background power.

115 The term $P_{bkg}(\lambda)$ is the background optical signal from the atmosphere, i.e. the brightness of the sky that is independent of the range. Usually it can be determined as the mean value of the LiDAR signal in a range far enough that the expected contribution from atmospheric backscatter is negligible. In Eq. 1, we decomposed both the backscatter coefficient $\beta(\lambda, z)$ and the atmospheric transmissivity $T(\lambda, z)$ into their molecular and particle components (denoted by the subscripts m and p, respectively):



$$\beta(\lambda, z) = \beta_m(\lambda, z) + \beta_p(\lambda, z),$$

120

$$T(\lambda, z) = T_m(\lambda, z) \cdot T_p(\lambda, z).$$

(2)

The attenuated backscatter signal (ABS) is therefore obtained by subtracting the background signal, multiplying by the square of the range z and dividing by the calibration constant K :

$$\begin{aligned} ABS(\lambda, z) &= \frac{(P(\lambda, z) - P_{bg}(\lambda)) \cdot z^2}{K} \\ &= \frac{P_{rcs}(\lambda, z)}{K} \end{aligned}$$

(3)

125 The quantity $P_{rcs}(\lambda, z)$ is commonly referred to as the range-corrected signal (RCS), while the ABS is obtained by calibrating the RCS through the system calibration constant K .

Accordingly, MIPA operates directly on the range-corrected signal (RCS), without requiring calibrated attenuated backscatter profiles, since the retrieval mainly relies on the spatial and temporal organization of the backscatter field.

3 Measurements campaign and datasets

A measurement campaign focused on the characterization and the study of the Atmospheric Boundary Layer took place at
130 CIAO (40.60°N, 15.72°E, 760 m) from 15 April 2024 to 30 June 2024. The campaign has been organized within the framework of ITINERIS - Italian Integrated Environmental Research Infrastructures System (<https://itineris.cnr.it/>, accessed on 9 July 2026). During the campaign, different types of remote sensing instruments operated simultaneously and continuously 24/7. Additionally, frequent radiosondes launches were performed, in order to establish a robust reference dataset for the ABLH retrieval. More details about the campaign can be found in (D'Amico et al., 2025). Here we just recall briefly that this event was
135 the ideal testbed to evaluate how different types of remote of sensor instruments can be used to monitor the ABLH continuously. Depending on the instrument involved, ABLH retrieval methods are based on different assumptions. For LiDAR and ceilometer measurements, for example, atmospheric aerosols are used as tracers of the ABL. However, if the ABL is not well mixed or in the case of precipitation, this assumption may show some limitations. Moreover, ABLHs located below the LiDAR/ceilometer full overlap height are not detectable independently of the retrieval algorithm. This situation occurs typically during night-time
140 conditions, when the absence of solar activity makes the ABLH quite low (<100m above the ground). In addition, there are conditions under which the ABL is formed (non-turbulent, cloud-driven, convective, wind shear, etc.) where the use of sensors like Doppler LiDAR and cloud radar can help to evaluate the limitations of LiDAR and ceilometer retrieved ABLHs.

The remote sensing instruments operating during the measurement campaign were, two Doppler radars (MIRA35 and MIRA35C by Metek, Elmshorn, Germany), a Doppler LiDAR (Stream LineXR by Halo Photonics/Lumibird, Lannion, France),
145 two multi-wavelength Raman LiDARs (POLPO—POtenza Lidar for Particle Observations, M3DUSA—Mobile 3-Depolarization Measurement System for Aerosols both from Raymetrics, Athens, Greece) and three ceilometers (CL31 and CL51 by Vaisala,



Table 1. Selected case studies.

Case study	Start Date-Time [UTC]	End Date-Time [UTC]	Duration [h]
1	28 April 2024 03:00	1 May 2024 00:00	69
2	15 April 2024 00:00	16 April 2024 12:00	36
3	27 June 2024 19:00	29 June 2024 19:00	48

Vantaa, Finland, and CHM15k by Lufft, Fellbach, Germany), and a microwave radiometer (RPG-HATPRO-G5 by Radiometer Physics, Meckenheim, Germany).

In addition, a fairly frequent radiosonde launch schedule (up to 8 launches per day) has been adopted during specific campaign days using two CIAO radiosounding systems (by VAISALA, one of which is equipped with an automatic launcher). During such days, selected according to specific atmospheric conditions, up to 8 launches have been performed in order to build an appropriate and representative reference dataset against which to compare ABLHs retrieved by using other algorithms like MIPA. The exact scheduling of the launches has been evaluated case by case based on high-resolution weather model forecasts, with denser launches typically performed in correspondence with ABL transition times and during special events like dust intrusions.

Finally, a large set of in situ instruments were also operating continuously throughout the campaign, providing useful information for aerosol characterization at ground level. More information on such instrumentation is available in D’Amico et al. (2025); Madonna et al. (2011).

All CIAO remote sensing and in situ instruments are part of ACTRIS and are fully compliant with the corresponding ACTRIS requirements.

The three case studies summarized in Table 1 were considered.

The criteria used for this selection as well as the atmospheric characterization of the three cases are reported in D’Amico et al. (2025). Here, we briefly reiterate that the case studies are designed to meet, as closely as possible, all the criteria needed to provide an optimal LiDAR/ceilometer input dataset for MIPA, namely appropriate vertical and temporal resolution, continuous long-term observations, and a high or moderate SNR. Additionally, the selected cases fairly represent the possible atmospheric scenarios, ranging from clean, cloudless conditions (case study 3) to situations with higher aerosol loading and slight cloud-contamination (case study 1) to almost persistent low clouds and consistent aerosol load (case study 2).

Modern Aerosol High-power Lidars (AHLs) or ceilometers can easily provide a dataset fulfilling the requirements on vertical and time resolutions, as they can deliver continuous timeseries of attenuated backscatter (and/or range-corrected signal) with a temporal resolution of less than 1 minute (typically from 10 to 60 s), and a vertical resolution of a few meters (typically from 3.75 to 15 m). The other two requirements are kind of complementary between AHLs and ceilometers. Typically, the former offers a better SNR, but they do not always operate continuously 24/7. Typically, LiDAR observations are not available during rain events (when LiDAR measurements are not possible or very challenging) or while the instrument performs internal



calibration measurements (for example, dark measurements or depolarization calibration cycles). However, ceilometers operate
175 unattended and continuously under any atmospheric condition, but deliver signals with a sensible lower SNR.

For this reason, it is particularly interesting to evaluate the performance of MIPA on both of these sensor types. A complete
assessment of MIPA on AHLs has already been given in D'Amico et al. (2025) where, considering the same case studies
mentioned above, it is shown that MIPA can deliver ABLHs in good agreement with the reference dataset (obtained using
radiosounding data) under atmospheric conditions characterized by quite different aerosol loads.

180 This study represents a completion of the work begun in D'Amico et al. (2025) providing the evaluation of the MIPA
algorithm when applied to ceilometer observations taken for the same case studies considered for the AHLs measurements.

Both case studies 1 and 2 are characterized by intense dust intrusion in the lower troposphere influencing the normal ABL
diurnal cycle. However, case study 3 refers to a cleaner situation with much lower aerosol loads where the ABL dynamics
can be considered to be quite uncoupled from the rest of atmospheric contents. Additionally, case studies 1 and 3 are almost
185 cloud-free while case study 2 shows clouds below 6 km a.s.l. for the duration of the whole observation. Consequently, the
selected case studies provide a fairly heterogeneous and representative dataset that can be used to investigate the retrieval of
MIPA under conditions ranging from relatively low to relatively high aerosol load and from cloud-free to cloud-contaminated
datasets.

We used as a reference the ABLH values derived from high vertical resolution (5 m) radiosonde data, computed using the
190 algorithm presented in Liu and Liang (2010). The algorithm first identifies the ABL regime by considering the near-surface
thermal gradient (difference in potential temperature) between two pre-selected close levels. In this way (depending on specific
threshold values of this gradient), three different regimes are determined: the unstable regime (convective boundary layer),
stable regime (stable boundary layer), and neutral regime (neutral residual layer). For an unstable or neutral regime, the ABLH
is determined at the height at which an air parcel rising adiabatically from the ground becomes neutrally buoyant. This level is
195 considered as a first guess and is subsequently refined by applying a threshold criterion to the first derivative of the potential
temperature. For the stable regime, the ABLH is determined by applying specific thresholds to both the first derivative of the
potential temperature and to horizontal wind differences. More details about this algorithm can be found in Liu and Liang
(2010).

Table 1 in D'Amico et al. (2025) reports the ABLHs retrieved from all radiosoundings performed during the campaign using
200 the procedure described above. This dataset was used both for the optimization and the validation of MIPA based on AHL
and ceilometer observations. For the ceilometer analysis, the optimization was carried out independently for each instrument
through a systematic grid-search procedure, while the same reference dataset was subsequently used for the final validation.
For completeness and ease of reference, the same table is also reproduced in Appendix A.

4 MIPA description

205 MIPA has been designed as a robust tool to retrieve ABLH from lidar observations. All the results presented in this work have
been obtained using the MIPA version 1.0.0 available as public GitHub repository.



A key feature of MIPA is its ability to exploit the inherent spatial–temporal structure of two-dimensional LiDAR measurements, leveraging the continuity and topology of concatenated profiles rather than treating each profile independently, as is common in traditional algorithms that often neglect valuable information contained in the data’s spatiotemporal structure. It is worth mentioning that MIPA relies on the correlation between adjacent pixels within the time–height image; due to this, the algorithm does not require absolute calibration and can operate effectively even with uncalibrated signals, such as the range-corrected signal $P_{rcs}(\lambda, z)$ defined in Eq. 3. In general, this is not the case for traditional ABLH retrieval algorithms, which often rely on plain signal thresholding directly in the signal domain, as in (Melfi et al., 1985), or on spatial transforms such as derivatives or wavelet transforms (Brooks, 2003), and therefore depend on the absolute magnitude of the signal. The MIPA algorithm is illustrated by the flow chart in Figure 1, and each step will be briefly described in the following subsections. Since ceilometers are affected by incomplete overlap in the lowest part of the measured profile and ABL is located in the lower atmospheric region, two input parameters h_{start} and h_{stop} are considered. The analysis is restricted to the altitude interval between h_{start} and h_{stop} and the upper clipping percentile p is therefore computed only over this analysis interval.

4.1 Radiometric normalization

Backscatter signals acquired from LiDARs and ceilometers exhibit a wide dynamic range, which is typical of active remote sensing systems. To ensure robustness in subsequent processing, particularly for tasks like edge detection, a radiometric normalization step is applied. This involves percentile clipping, which limits extreme values and reduces the influence of outliers with minimal distortion to the structural features of interest, i.e., edges. This operation clamps the intensities of the pixels at the value corresponding to the chosen percentile p , effectively reducing the impact of very bright regions (typically clouds) while preserving the edges of the aerosol layer, thereby allowing their identification as potential candidates for ABLH in subsequent processing steps.

4.2 Vertical degradation

The next processing step reduces the vertical spatial resolution by down-sampling each column, i.e., corresponding to individual time measurements, independently. This is done using a low-pass filter implemented as a moving average. The filter window size controls the smoothing level and serves as the only tuning parameter, which is chosen to achieve a degraded vertical resolution of no finer than 70 m. This specific value was selected after a series of simulations designed to identify the optimal level of down-sampling. Since the three investigated ceilometers have different native vertical resolutions, e.g. 10 m for the CL51 and CL31, and 15 m for the CHM15k, the optimal value of r is naturally sensor-dependent.

4.3 Pre-processing

Afterwards, the down-sampled image goes through further processing based on image-based morphological operators.

Morphological image processing is a framework rooted in mathematical morphology and set theory, forming a family of non-linear image processing operations. It offers a unified and powerful approach to extract and analyze image components,

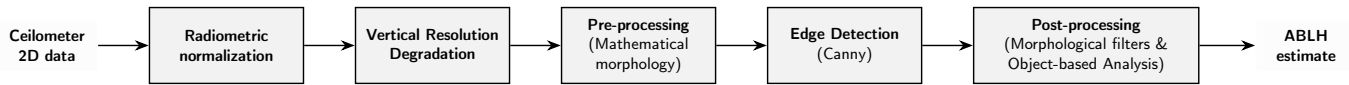


Figure 1. Processing chain of the MIPA algorithm.

e.g., shapes, boundaries, and structures that are useful for the representation, description, and understanding of objects within an image. Interested readers may refer to seminal books, such as *Digital Image Processing* by Gonzalez and Woods (Gonzalez and Woods, 2018) for an introduction to the topic. For more advanced treatments, work such as *Morphological Image Analysis* by Pierre Soille (Soille, 2003) provides a deeper exploration of the subject.

In this step of MIPA, the chosen morphological operator is a low-pass filter based on half-gradients, defined as the pointwise average of dilation and erosion. In particular, a directional morphological filter is applied using a horizontal line (aligned with the time axis) as the structure element (SE), its length denoted by l_{pre} . This step aims to smooth the image along the horizontal direction, where the ABL dynamics tend to evolve slowly. As a result, unwanted high-frequency fluctuations along the time axis are attenuated, whereas vertical edges, important for subsequent accurate detection of ABLH, are preserved.

4.4 Edge detection

Afterwards, an edge detector is applied to the pre-processed image. In MIPA, the classical Canny edge detector (Canny, 1986) is employed due to its simplicity and widespread availability in common software environments such as MATLAB and Python. The choice of Canny is motivated by its balance of simplicity and effectiveness. The Canny algorithm performs Gaussian smoothing to reduce noise, followed by gradient calculation, non-maximum suppression, and hysteresis thresholding to robustly identify edges. It is important to note that the choice of edge detector is not exclusive; other edge detection operators or maximum likelihood (ML) detectors could also be used, particularly when the statistical characteristics of edge/non-edge signals and noise are known, potentially improving detection accuracy, (Rosenfeld and Banerjee, 1992). The detected edges are marked with 1, while the rest of the map is marked 0. All pixels labeled 1 are considered potential candidates to represent the ABLH.

4.5 Post-processing

Finally, the detected edge map is subjected to further analysis using signal processing techniques, including an additional morphological filtering step and an object-based image analysis (OBIA) approach.

4.5.1 Morphological filters

Once again, image morphological operators are employed in the post-processing stage. Specifically, a directional morphological filter is applied to remove unrealistic edges, i.e. those that fluctuate too rapidly compared to the typical dynamics of the



ABL. This is accomplished through a series of directional low-pass morphological filters created by sequentially applying opening and closing operations. In this case, the SE is a line with length l_{post} and orientation angle θ relative to the horizontal axis. The angle θ is varied within a predefined range from θ_{min} to θ_{max} to effectively capture and smooth edges in different directions.

4.5.2 Object-based analysis

Whenever the spatial resolution of remote sensing data increases to the point where objects of interest span multiple pixels, traditional pixel-based methods become less effective, as individual pixels no longer correspond to meaningful objects. OBIA overcomes this limitation by grouping pixels into meaningful objects based on their features, e.g., spectral, spatial, and contextual, thus enabling more accurate information extraction. Interested readers can refer to Blaschke et al. (2008) and Blaschke (2010) for detailed information on OBIA and its potential remote sensing applications.

In the context of MIPA, the object-based approach consists of grouping edge pixels into spatially continuous regions, referred to as objects. Two edge pixels are considered part of the same object if they are spatially connected through an 8-connected neighborhood, meaning that they share either a side or a corner.

Once all connected edge pixels have been aggregated, each resulting object is characterized by its mean height and temporal extension. Objects with a temporal extension smaller than a predefined threshold are considered potentially unreliable and are therefore compared with neighboring objects.

For each candidate object, the absolute vertical distance between its mean height and the mean heights of neighboring objects is computed. Objects whose distance exceeds the predefined threshold δ_{post} are identified as inconsistent with the surrounding structures and are therefore removed from the set of ABLH candidates.

The threshold δ_{post} is derived from a reference threshold δ_0 defined at the original instrument resolution and scaled by the vertical down-sampling factor r :

$$\delta_{post} = \text{round}\left(\frac{\delta_0}{r}\right) \quad (4)$$

where $\text{round}(\cdot)$ denotes rounding to the nearest integer value. The parameter δ_0 represents the maximum allowed vertical distance, expressed in bins at the original instrument resolution, while δ_{post} is the corresponding threshold used on the down-sampled image.

Finally, the ABLH estimate is obtained by interpolating the remaining validated objects.

5 Experimental Setup

The input dataset used in this study consists of the standard products delivered by the CHM15k, CL31, and CL51 ceilometers corresponding to the three case studies introduced in Section 3.



Table 2. Overview of ceilometers sensor parameters.

Parameter	CHM15k	CL51	CL31
Manufacturer	Lufft	Vaisala	Vaisala
Time resolution (s)	15	16	15
Vertical resolution (m)	15	10	10
Wavelength (nm)	1064	910	910
Range (km)	15	10	7.5
PRF (kHz)	5-7	6.5	10
Pulse energy (μJ)	8	3	1.2
RFOV (mrad)	0.23	0.56	0.83

More specifically, the proprietary software supplied with CHM15k (firmware version 1.130) saves all measured backscatter profiles in a daily NetCDF file using the variable *beta_raw(time, range)*. This variable represents the input dataset that we considered for MIPA and contains the internally normalized range corrected signal measured by the instrument, integrated over a 15 s time period and sampled at a vertical resolution of ≈ 15 m.

For the Vaisala ceilometers CL31 and CL51, we used as input the Level-2 NetCDF files produced by the proprietary software BL-View (version 2.1). These files contain a variable called *profile_data(timeDim, range)* that provides the signal backscatter profile sampled at a vertical resolution of 10 m and integrated over 15 s for CL31 and 16 s for CL51.

All the datasets we considered refer to vertically pointing observations and are corrected internally for overlap. Actual raw data (without any instrumental correction applied) are not available for any of the three considered ceilometers. This represents an intrinsic limitation of the present study, as the proprietary, “black-box” nature of both the internal overlap-correction procedures and the vendor-specific ABLH retrieval algorithms precludes a fully transparent methodological comparison and prevents fully independent processing of the raw optical signal.

Nevertheless, these products correspond to the standard operational outputs available to end users and therefore represent the most relevant dataset for evaluating the practical applicability of MIPA to commercial ceilometer observations.

6 Results and Discussion

As explained in Section 4, MIPA requires the setting of several parameters defining crucial aspects of the algorithm, like the initial vertical down-sampling of the input dataset, the valid altitude range, the shape of the morphological filter applied in the pre-processing step, the optimization of the edge detector, and finally, the behavior of object-based image analysis implemented in the post-processing phase. In the following, the term “MIPA configuration” denotes the specification of the complete set of required input parameters.



Table 3. MIPA parameter configuration adopted for each investigated ceilometer.

Parameter	Optimized values		
	CHM15k	CL51	CL31
r	5	7	7
p	77	74	71
h_{start}	285	130	40
h_{stop}	7000	7000	7000
l_{pre}	3	3	3
l_{post}	4	4	4
θ_{min}	-66°	-66°	-66°
θ_{max}	+66°	+66°	+66°
δ_{post}	20	14	14

As the final ABLH estimates provided by MIPA depend on the selected processing parameters, an optimization strategy is required to identify the most suitable configuration. In general, the optimal parameter values may depend on the characteristics of the input dataset, particularly when different types of sensors are considered. Nevertheless, one of the main strengths of MIPA is its limited dependence on the absolute intensity values of the input signal. Therefore, only a small subset of the algorithm parameters is expected to require instrument-specific tuning. To verify this assumption, a systematic grid search was performed over the selected MIPA parameters. Specifically, the parameter p was varied from 60 to 100 with a step of 1, while the lower boundary of the analysis region, h_{start} , was varied from 0 to 450 m with a step of 15 m for the CHM15k, and from 0 to 300 m with a step of 10 m for the CL31 and CL51 ceilometers. This resulted in a total of 1,271 parameter combinations evaluated for each instrument. For each parameter combination, MIPA was executed on the three selected case studies, and the retrieved ABLH values were compared with the corresponding radiosonde-derived reference values. The performance of each configuration was quantified through the RMSE computed with respect to the radiosonde-derived reference dataset for the three selected case studies. The optimal configuration was defined as the one minimizing this average RMSE. The optimization procedure was carried out independently for each of the three ceilometer types considered in this work. The resulting optimal parameter values are reported in Table 3.

For all the ceilometers considered, we found the same optimal values for the parameters defining the structuring element of the morphological filters used in both pre-processing and post-processing phases (i.e. l_{pre} , l_{post} , θ_{min} and θ_{max}). Additionally, the same values were found to be the optimal one also when High Power LiDARs (HPLs) are considered (D'Amico et al., 2025). This is a clear indication that the optimized shape of the structuring element of the applied morphological filters seems to be more related to the typical variability of atmospheric aerosols than to the specific sensors used to perform the measurements.



The parameter r defines the vertical down-sampling applied during the pre-processing stage and, as described in Section 4.2, corresponds to the width, expressed in range bins, of the sliding averaging window. It should be noted that the native vertical resolution is 10 m for the CL31 and CL51, whereas it is 15 m for the CHM15k. Consequently, although the optimal values of r reported in Table 3 differ between the Vaisala and Lufft instruments, they correspond to nearly the same effective vertical resolution after down-sampling (approximately 70–75 m). This suggests that the optimal vertical scale of the smoothing operation is largely independent of the specific sensor and is instead related to the characteristic vertical scales of the atmospheric boundary layer. However, as reported in D’Amico et al. (2025), the optimization performed on HPLs resulted in a less aggressive down-sampling (approximately 20 m), suggesting that the optimal value of r is also influenced by SNR. The remaining parameters, namely p , δ_{post} , and h_{start} , appear to exhibit a stronger instrument dependence. In particular, both the clipping percentile p and the object-based post-processing threshold δ_{post} are influenced by the SNR of the input signal, whereas p is also affected by the radiometric dynamic range of the measurements. Conversely, h_{start} mainly depends on the reliability of the measurements in the lowest portion of the atmospheric profile and, therefore, can be connected to the full overlap height of the specific instrument. In general, the optimal clipping percentile tends to decrease as the SNR decreases. Among the three ceilometers considered, the CHM15k provides the highest signal-to-noise ratio, whereas the CL31 exhibits the lowest SNR. Consequently, a more aggressive clipping (i.e., a lower clipping percentile) is required for noisier measurements in order to reduce the influence of noise fluctuations while preserving the atmospheric structures of interest, thereby reducing the probability that noise features are detected as edges. Finally, the optimal value of h_{start} is also instrument dependent because ceilometers generally are characterized by different full overlap height. It has to be noted that no reliable estimation of the full overlap height is available for any of the considered ceilometers. This is the reason for which we decided to include h_{start} in the optimization. On the other hand, if a reliable estimation of the full overlap height is available, h_{start} can be set to such value. The parameter h_{stop} was not included in the optimization procedure and was fixed to 7000 m for all the investigated ceilometers. This value was selected because it is well above the altitude range where the atmospheric boundary layer is expected to develop, while at higher altitudes the backscattered signal is generally strongly attenuated. Therefore, extending the processing to larger ranges would not provide additional information for ABLH retrieval while unnecessarily increasing the computational cost.

The resulting MIPA parameter configurations adopted for the three investigated ceilometers are reported in Table 3.

Figure 2 shows the ABLH retrieved by MIPA (red curve) when applied to the dataset measured by the three considered ceilometers for the three selected case studies. The input data set is also displayed in the same figure as a colormap. The reference ABLH dataset obtained from the radiosonde data is reported as gray dots.

Similarly to what happens when MIPA is applied to HPL observations, also for the ceilometers there is a general overestimation of MIPA retrieved ABLH in night-time conditions. As explained in D’Amico et al. (2025), this discrepancy can be explained by considering that if the ABLH is located below the full overlap height, the ABLH delivered by MIPA refers to the top of the first detected aerosol layer. This situation may occur typically in night-time conditions, where the ABLH is relatively low due to the absence of solar convective activity. However, in general, ceilometers are characterized by a lower full overlap height than HPLs because they usually are equipped with smaller telescopes.

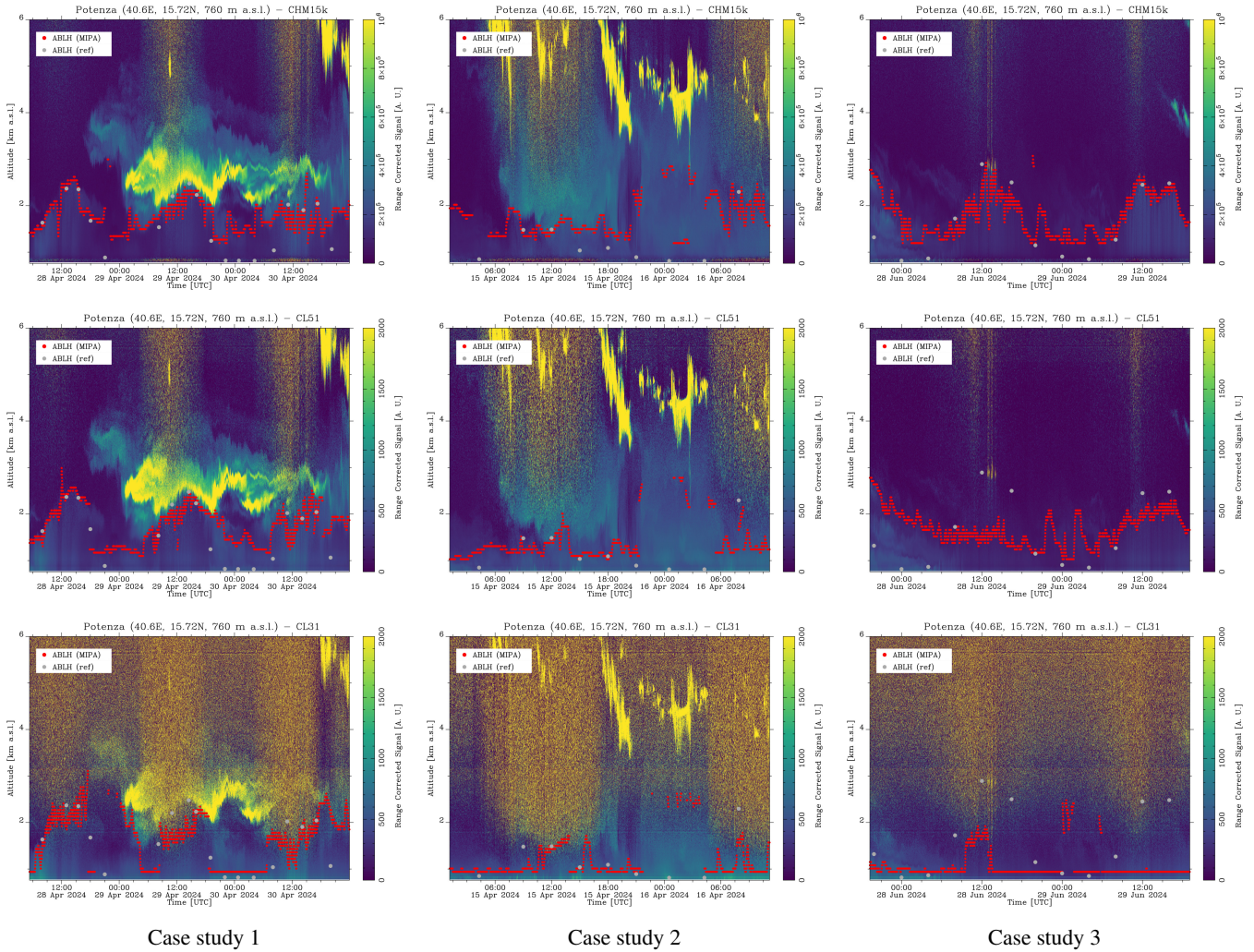


Figure 2. Case study 1 (on the left), 2 (central column) and 3 (on the right): range-corrected signal measured by CHM15k (top row), CL51 (middle row), and CL31 (bottom row). The red curve shows the ABLH as retrieved by MIPA, while the gray dots are the reference ABLH calculated from radiosoundings.

365 This effect is particularly evident for the CHM15k, which may indicate either an imperfect overlap correction or instrument instabilities. This interpretation is also supported by previous studies reporting temperature-dependent variations of the overlap function for this instrument Hervo et al. (2016). Furthermore, the optimization procedure resulted in a significantly higher value of h_{start} for the CHM15k than for the other ceilometers, suggesting that a larger portion of the lowest range bins should be excluded from the analysis.

370 However, the CL31 and CL51 ceilometers seem to perform better during night-time conditions, providing ABLH estimates closer to the reference values.



Table 4. Statistical analysis of the difference ($\Delta = h - h_{ref}$) between reference ABLH values (h_{ref} and the corresponding one retrieved (h) by MIPA and by the internal algorithm for the ceilometers CHM15k, CL51 and CL31. The mean (Δ_{mean}), the standard deviation (Δ_{SD}), the standard error (Δ_{SE}), the median (Δ_{med}), the mean square difference (Δ^2_{mean}), the minimum (Δ_{min}) and the maximum (Δ_{max}) differences are given. N is the number of points on which the statistics are carried out. The reference is assumed to be the ABLH calculated from the co-located radiosoundings. For comparison, the last column on the right reports the values shown in Table 3 in D’Amico et al. (2025) referring to the MIPA analysis made on high power LiDAR POLPO for the same case studies (see the text for more details).

	CHM15k		CL51		CL31		POLPO
	MIPA	Internal	MIPA	Internal	MIPA	Internal	
Δ_{mean} (m)	234	795	81	291	-285	-115	98
Δ_{SD} (m)	442	663	556	847	561	884	366
Δ_{SE} (m)	74	114	91	136	92	141	63
Δ_{med} (m)	111	889	62	1	-152	-56	27
Δ_{min} (m)	-426	-397	-1303	-956	-1560	-2063	-713
Δ_{max} (m)	1300	1963	1320	2740	1065	2404	948
Δ^2_{mean} (m ²)	244446	1057876	307090	783219	387547	773977	139942
N	36	34	37	39	37	39	34

For all the ceilometers considered, the accurate retrieval of the ABLH seems to be more challenging for case study 3. It is important to note that case study 3 is characterized by the cleaner situation in terms of aerosol load compared to the other two selected cases. In such conditions, the SNR of the input dataset plays a crucial role, as the backscattered signal is typically low and can be drastically covered by noise. This is evident when considering the retrieval obtained for case study 3 with the CL31 ceilometer (the one characterized by the lowest SNR among the three considered): the typical ABL diurnal cycle is almost completely missed, as MIPA retrieves a nearly flat ABLH throughout the entire observation period.

Both case studies 1 and 2 are characterized by intense dust intrusions, resulting in a relatively high concentration of aerosol particles in the atmosphere. These conditions significantly increase the SNR of the atmospheric backscatter signal and, consequently, enable accurate ABLH retrieval even with relatively low-power instruments such as the CL31 ceilometer.

It is worth recalling that any algorithm for retrieving the ABLH from LiDAR observations (including MIPA) relies on the presence of atmospheric tracers within the boundary layer. Therefore, the larger the amount of tracers, the more accurate the retrieved ABLH is expected to be. Consequently, particularly clean atmospheric conditions generally represent the most challenging scenario for aerosol-based ABLH retrieval.

A statistical analysis of the differences of ABLHs retrieved by MIPA with respect to the corresponding (in time) reference is given in Table 4. In this Table the mean (Δ_{mean}), the median (Δ_{med}), the standard deviation (Δ_{SD}), the standard error (Δ_{SE}), the mean square difference (Δ^2_{mean}), the minimum (Δ_{min}) and the maximum (Δ_{max}) of the differences between

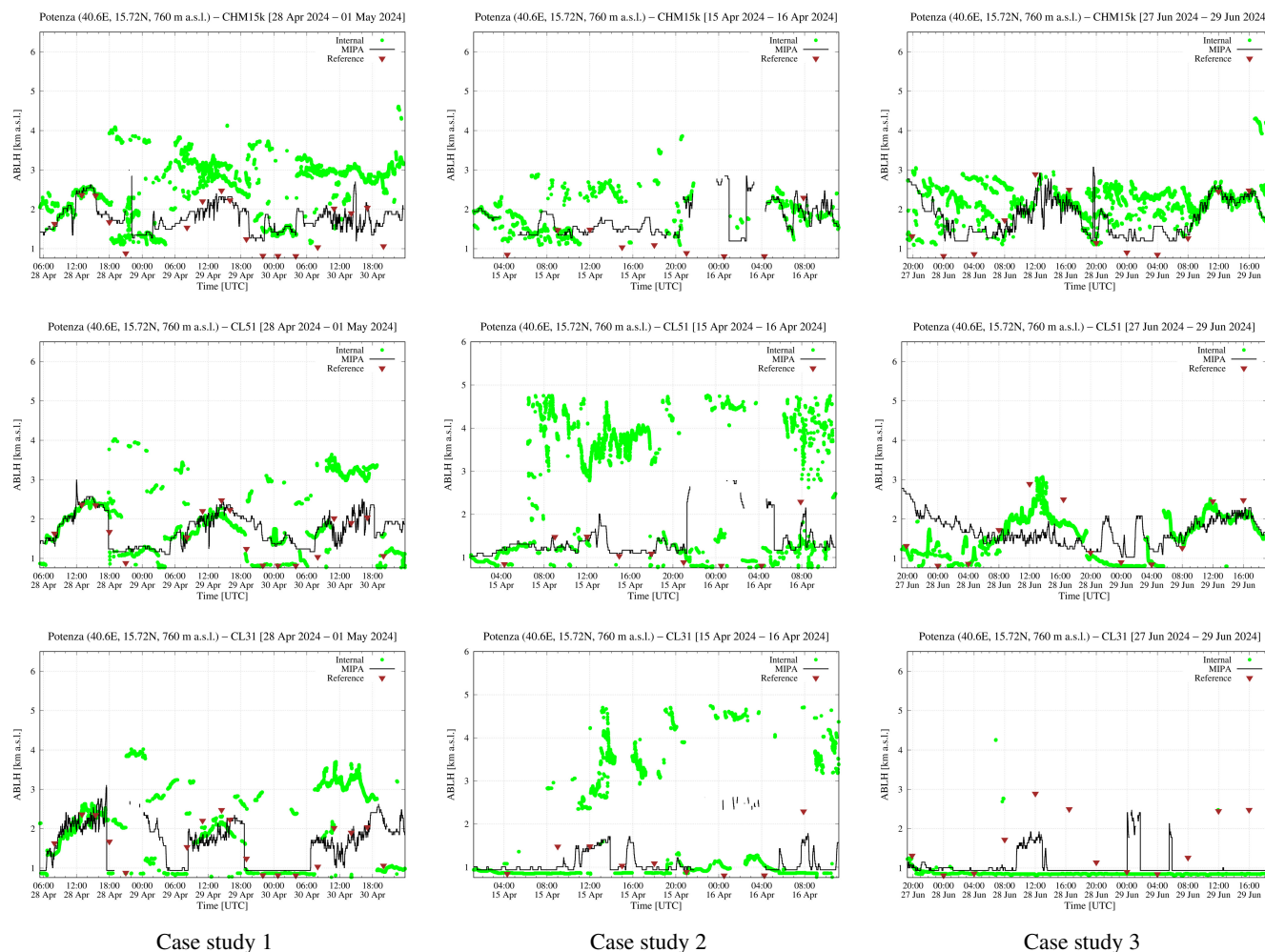


Figure 3. Case study 1 (on the left), 2 (central column) and 3 (on the right): ABLH calculated by MIPA (black curve) for CHM15k (top row), CL51 (middle row) and CL31 (bottom row). Green dots represent the value of ABLH with the highest quality score internally calculated by each ceilometer with proprietary algorithm. Brown triangles are the reference ABLH calculated from radiosoundings.

ABLH retrieved by MIPA and the corresponding reference points are reported (Foken, 2021). It is important to note that the typical uncertainties associated with radiosonde-derived ABLH estimates generally range from approximately 100 m to 200 m. Consequently, statistical differences that fall within this interval should be interpreted with caution, as they may originate from the intrinsic spatial drift of the radiosonde and the underlying thermodynamic assumptions employed in the retrieval, at least as much as from the inherent limitations of the optical retrieval techniques themselves. It should be noted that the number of MIPA retrievals may be slightly lower than the number of available radiosonde observations, since under some atmospheric conditions a reliable ABLH estimate cannot always be obtained from the ceilometer observations.



395 According to this analysis, the CHM15k provides the best overall agreement with the radiosonde-derived ABLH, as indicated by the lowest RMSE and standard error. The CL51, on the other hand, exhibits the smallest mean bias, whereas the CL31 generally shows the largest retrieval errors, likely due to its lower signal-to-noise ratio under low aerosol load conditions.

Additionally, we compared the ABLH retrieved by MIPA with the ABLH calculated by the three ceilometers using their proprietary algorithms (in this paper, calculated internally). All considered ceilometers provide three different candidates for the ABLH, each of them with a corresponding quality score. Figure 3 provides a comparison of the MIPA retrieved ABLHs against the ABLHs calculated internally by each ceilometer with the highest quality score. It is evident that on average in all cases the ABLH provided by MIPA are in better agreement with the reference values with respect to the ABLH best estimates provided by the three ceilometers. However, especially for the two Vaisala ceilometers, it seems that the ABLHs calculated internally perform better than MIPA under night-time conditions. One of the reasons for this better agreement could be that the
405 ceilometers use different input data (not available) from the ones considered here. In addition, all details of the algorithm used by the ceilometers to obtain ABLH are not documented.

The overall better performance of MIPA with respect to the internal algorithms for the retrieval of the ABLH is also confirmed by the values reported in Table 4 where the same statistical analysis performed on MIPA is also provided for the internally retrieved ABLH (column "Internal"). In all the cases MIPA provides sensible lower mean square difference suggesting
410 an overall better agreement with the reference values.

It is interesting to compare the MIPA results obtained in this study with those described in D'Amico et al. (2025). In the latter study, the authors report the analysis of the MIPA applied to the measurements made by the high power LiDARs POtenza Lidar for Particle Observations (POLPO) for the same case studies and using the same reference dataset considered here. The last column of Table 4 provides the statistical analysis for the POLPO wavelength closest to those of the three ceilometers
415 (1064 nm).

By comparing the results obtained for POLPO with those retrieved for the three ceilometers, the advantages of using High Power LiDARs rather than low-power LiDARs for accurate MIPA-based ABLH retrieval become evident. Overall, all the considered statistical indicators show better performance for POLPO. In particular, the RMSE is reduced by a factor ranging from approximately 1.3 to 1.7. Nevertheless, it should be emphasized that ceilometers are considerably more widespread than
420 HPLs because they are generally less expensive, easier to operate, and designed for continuous 24/7 operation. Moreover, they are typically characterized by smaller telescopes and a larger field of view, allowing, in principle, a better observation of the atmospheric region close to the ground, where the ABLH is often located, especially during night-time conditions.

7 Conclusions

In this study, we investigated the application of the Morphological Image Processing Approach (MIPA) to retrieve the Atmospheric Boundary Layer Height (ABLH) from ceilometer observations. The study was conducted within the framework of a
425 dedicated measurement campaign carried out at CIAO and focused on the evaluation of different ABLH retrieval techniques. During the campaign, three ceilometers (the CHM15k from Lufft and the CL31 and CL51 from Vaisala) operated continuously



together with other atmospheric sensors and two radiosounding systems. To provide a robust assessment of the algorithm, three case studies characterized by different atmospheric conditions, ranging from intense dust intrusions into the boundary layer to clean atmospheric conditions, were selected. Furthermore, an intensified radiosonde launching schedule was adopted during these periods to establish a reliable reference dataset. A systematic grid search was performed to optimize the MIPA configuration independently for each ceilometer. The optimal configuration was defined as the one minimizing the discrepancies between the ABLH retrieved by MIPA and the corresponding radiosonde-derived reference values over the three selected case studies. The optimized configurations also provided useful insights into the dependence of the algorithm parameters on the characteristics of the different instruments. The comparison between the optimized MIPA retrievals and the radiosonde-derived ABLH showed good agreement during daytime conditions for the first two case studies, which were characterized by relatively high aerosol loads. During night-time, different behaviors were observed depending on the ceilometer model. In particular, the CHM15k generally overestimated the ABLH, whereas the discrepancies were smaller for the CL31 and CL51. This behavior suggests that the CHM15k measurements are more strongly affected by uncertainties in the lowest part of the atmospheric profile, possibly related to overlap correction and/or instrument instabilities. This interpretation is also supported by the optimization results, which selected a significantly larger value of h_{start} for the CHM15k than for the other two instruments. The third case study, characterized by very clean atmospheric conditions, proved to be the most challenging for all the considered ceilometers. As expected, the largest discrepancies were observed for the CL31, which provides the lowest signal-to-noise ratio among the investigated instruments. The relatively low SNR makes the application of MIPA more difficult under low aerosol load conditions, whereas the CHM15k and CL51 appear to be more suitable for accurate ABLH retrievals in such scenarios. Overall, when the three case studies are considered together, the CHM15k provides the best overall agreement with the radiosonde-derived ABLH, as indicated by the lowest RMSE and standard error, whereas the CL51 exhibits the smallest mean bias. While the CHM15k benefits from a higher SNR than the CL31, the CL51 likely benefits from improved near-range measurement capability, resulting in a lower systematic bias. Conversely, the lower performance of the CL31 is mainly associated with its lower SNR, particularly under clean atmospheric conditions.

It is worth noting that MIPA is also well suited for near-real-time ABLH retrieval at the network level. Benchmark tests performed on CHM15k, CL31, and CL51 datasets showed a remarkably consistent computational cost of approximately 0.93 ms per vertical profile (corresponding to 0.21–0.23 s per hour of observations), highlighting the algorithm's computational efficiency and scalability across different ceilometer systems. The test were made on a system equipped with an AMD processor (EPYC 7713 64-Core Processor 2.00 GHz Dual Core) and with a 2,00 TB installed RAM.

Future research should further evaluate the feasibility of implementing an independent, experimentally derived characterization of the CHM15k overlap function in order to reduce or correct measurement artifacts arising from proprietary instrument correction algorithms and temperature-dependent instrumental instabilities. Finally, the ABLH retrieved by MIPA was compared with the corresponding ABLH internally estimated by the proprietary algorithms of the three ceilometers. On average, MIPA showed a better agreement with the radiosonde-derived reference dataset, demonstrating that the proposed methodology can provide more accurate and consistent ABLH estimates than the operational algorithms implemented by the manufacturers. Since MIPA has now been successfully assessed on both High Power LiDARs and commercial ceilometers, its applicability to



integrated multi-sensor observing systems can now be envisaged. In particular, ceilometer observations could complement non-continuous HPL measurements by providing continuous ABLH retrievals between LiDAR acquisitions while simultaneously
465 improving the characterization of the nocturnal boundary layer. Moreover, owing to the widespread deployment of ceilometers within operational monitoring networks, the proposed MIPA-based multi-sensor approach represents a promising solution for improving atmospheric boundary layer monitoring across local, regional, continental, and potentially even global scales.

Appendix A

Table A1 provides the reference dataset used in this study. It summarizes the ABLHs retrieved from all the radiosoundings
470 available for the selected case studies. Compared with Table 1 in D’Amico et al. (2025), two additional radiosoundings (28 April 2024 at 04:00 UTC and 29 April 2024 at 14:28 UTC) are included here because corresponding ceilometer observations were available, whereas no concurrent High Power LiDAR measurements were available for the previous study.

Table A1. Radiosoundings performed during the selected case studies. Compared with Table 1 in D’Amico et al. (2025), two additional radiosoundings (28 April 2024 at 04:00 UTC and 29 April 2024 at 14:28 UTC) are included. The soundings are grouped by day. For the reader’s convenience, ABLHs are reported both in meters above sea level (a.s.l.) and above ground level (a.g.l.). The measurement site altitude is 760 m.

Date	Time UTC [hh:mm]	ABLH (m)	
		a.s.l.	a.g.l.
15 April 2024	04:18	849	89
	09:00	1480	720
	12:00	1487	727
	15:00	1037	277
	18:00	1092	332
	21:00	892	132
16 April 2024	00:30	812	52
	04:15	813	53
	07:54	2296	1536
28 April 2024	04:00	858	98
	08:00	1634	874
	13:00	2368	1608
	15:30	2351	1591
	18:00	1676	916
	21:00	885	125



Table A1. Continued.

Date	Time UTC [hh:mm]	ABLH (m)	
		a.s.l.	a.g.l.
29 April 2024	08:10	1537	777
	11:00	2205	1445
	14:28	2478	1718
	16:00	2232	1472
	19:00	1244	484
	22:00	822	62
30 April 2024	00:45	819	59
	04:00	816	56
	08:00	1039	279
	10:59	2022	1262
	14:07	1904	1144
	17:03	2043	1283
	20:00	1065	305
27 June 2024	19:53	1320	560
28 June 2024	00:00	818	58
	04:00	865	105
	08:00	1724	964
	12:01	2893	2133
	16:27	2500	1740
	20:00	1148	388
29 June 2024	00:00	906	146
	04:00	850	90
	08:00	1268	508
	12:00	2451	1691
	16:00	2482	1722



Code and data availability. The data used in this paper are freely available: <https://doi.org/10.5281/zenodo.21450635>. The MIPA code is available as GitHub repository: <https://github.com/actris-ares/MIPA> (accessed on 20 July 2026).

475 *Author contributions.* Conceptualization, G.D. and G.V.; data curation, A.M., G.V. and G.D.; formal analysis, G.D., A.M. and G.V.; investigation, G.D., A.M. and G.V.; writing—original draft, A.M. and G.D.; writing—review and editing, all authors. All authors have read and agreed to the published version of the manuscript.

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