

GRAPH-BASED TRACING OF THE ATMOSPHERIC BOUNDARY LAYER BY A CEILOMETER: A CASE STUDY

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Abstract

The atmospheric boundary layer (ABL) is an important factor in the atmospheric processes. It serves as an intermediary between the earth's surface and the atmosphere in the exchange of mass, energy, and momentum. ABL height (ABLH) also restricts the dispersion volume of atmospheric pollutants. The ABLH can be retrieved from lidar and ceilometer (low power lidar) backscatter profiles by tracing the increased aerosol loading associated with ABL. Numerous lidar-based algorithms are currently implemented, but their ability to trace ABL evolution is often limited. The main issues are related to the selection of the correct layer when multiple aerosol layers are present. To overcome the problem, we employ a graph-based approach to post-process already identified ABL candidates (determined by the gradient in ceilometer backscatter) in two cases. A simple non-parametric smoothing method was also utilized for comparison. Our findings indicate that the graph-based algorithm is superior to the smoothing method in obtaining a consistent tracing of the diurnal evolution of ABL over Sofia, although some issues were also encountered during the evening ABL transition.

Key words: atmospheric boundary layer, graph, shortest path, lidar, ceilometer

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Introduction. The atmospheric boundary layer (ABL) is the lowest part of the atmosphere, where the latter interacts with the Earth's surface [1]. ABL is a key parameter for the accuracy of numerical weather prediction models [2], and it also determines the distribution of airborne pollutants [3–5]. Several studies focusing on observations, parameterizations, and applications of the ABL have also been carried out in Bulgaria [6]. Despite its importance, the operational measurement of the ABL height poses challenges due to its significant spatial and temporal variability [7,8]. The use of ground-based remote sensing instruments has demonstrated promising results in tracing the development of ABL [9]. Thanks to recent advances in methods and algorithms based on proxy data for the structure of ABL, the tracing of the latter in near real time is getting feasible [10].

Originally designed to determine cloud base height, ceilometers provide vertical profiles of the backscattered signal from atmospheric aerosols that can be used as tracers for the evolution of the ABL [11]. Ceilometer software provides range-corrected signal (RCS) that is used to detect the ABL height (ABLH); a review of the available algorithms can be found in [12]. Some of the methods locate the zone between the ABL and the free atmosphere by the presence of a gradient in the aerosol loading resulting in a gradient in the RCS, others rely on the variation in the signal associated with the entrainment zone, also there are algorithms based on wavelet covariance, etc [13]. More advanced algorithms take into account both vertical gradients and temporal variations [14].

An inherent challenge for all lidar-based methods in ABLH retrieval is not the detection of gradients in the aerosol loading, but their attribution to the structure and dynamics of the ABL. Recently, graph-based algorithms [15–17] have emerged that promise to solve the problem. The ABLH tracing in these methods is accomplished by finding the shortest path [18] through potential ABLH candidates. Operating within the signal space these algorithms find the shortest path between two points by accounting for distances using weights (e.g., in [15] the weight is defined as the negative and reciprocal of the vertical gradient in the RCS, while in [16,17] the variations in the RCS are also considered).

The aim of the study is to demonstrate the potential of a new graph-based algorithm in ABLH retrieval that operates in real space of ABL height candidates. The method allows ABL tracing by minimization of the discrepancy in consecutive ABL heights providing smooth and reasonable daily evolution of the ABL. The results are compared against raw as well as additionally smoothed output from a freely available algorithm considering both vertical gradients and temporal variations in the signal.

Data and methods. This study uses RCS profiles obtained from a Lufft's (formerly Jenoptik) CHM15k ceilometer recorded in the summer of 2015. The CHM15k is a biaxial ceilometer that operates at a wavelength of 1064 nm, emitting laser pulses with an energy of 8 μ J. The ceilometer has a range of 15 km and a resolution of 15 m. It is set to record a backscatter profile every minute.

Potential ABLH candidates are obtained through the processing of the RCS using the freely available Structure of the Atmosphere (STRAT) algorithm [14]. The algorithm combines the temporal variations and the vertical gradients in RCS via Sobel 2-D derivation operator, providing three global gradients – the strongest, the second strongest, and the lowest-high, which are reported as ABLH candidates [13]. These three candidates, along with the cloud base height of the lowest cloud layer (obtained from the ceilometer’s software) are organized as vertices in three separate graphs. The first graph spans from 0:00 to 8:00 UTC, the second – from 8:00 to 14:30 UTC (roughly when the maximum of the ABLH over Sofia is observed) and the third – from 14:30 to 24:00 UTC. It is worth noting that the selection of time intervals dividing the day into three segments is based on the expected periods when stable and convective ABLs are likely to be observed. Although there is some flexibility in this choice of breakpoints, if one wants to capture both the shallow and the deep ABL, the first point should be around the morning transition (the minimum of ABLH), while the second should be in the afternoon when ABLH reaches its maximum and often tends to remain relatively constant until the evening transition.

Each vertex from a given graph is connected to the vertices within a search window (SW) (as shown in Fig. 1). The SW of the graphs has widths of 120, 60, and 120 minutes, respectively. The allowed edges for the second graph span a shorter period because the dynamics of convective ABL is more intense, and more significant changes in the ABLH are likely to occur. One might be tempted to choose a shorter search window that might reveal more details in the development of the ABL, but such an approach risks algorithmic failure, as traversing the graph

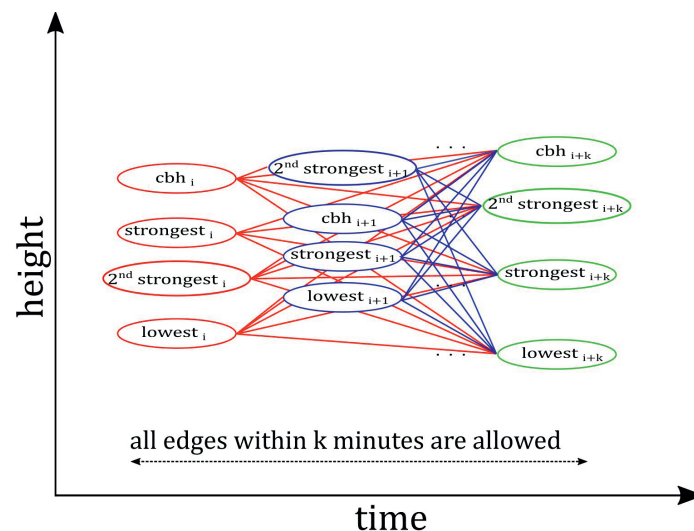


Fig. 1. The search window of a graph determines all edges (connections between two vertices) that can be established

may become impossible. Conversely, choosing a wider window results in increased computational requirements and may lead to excessive ABL height smoothing. The selected search windows ensure smoother changes in ABLH and correspond to the typical ABL time scale – about an hour.

The cost function that needs to be minimized to determine the shortest path through each graph is based on Euclidean distance. It is square root of the sum of the squared vertical distance between two vertices and the squared product of the time interval and ABL characteristic growth rate (5 m/min, 15 m/min and 5 m/min are used here). The greater the growth rate is the more penalized longer edges are. The last vertex of the current graph and the first one of the next graph are seamed to avoid abrupt changes from one graph to the next.

Additionally, a nonparametric statistical approach [19] was applied, resulting in the smoothed best STRAT candidates (composed of the lowest nighttime gradients and the strongest daytime gradients). A qualitative comparison between graph-based and smoothing-based ABLHs is performed for two days in the summer of 2015, characterized by convective ABL development, as discerned from the ceilometer's RCS.

Results. The performance of the algorithms is demonstrated in certain cases without precipitation. The first case study, conducted on July 22, 2015 – a day with clear skies and a distinctive daily evolution of the ABL. The STRAT ABLH candidates (the strongest gradient, the second strongest gradient, and the lowest gradient) as well as cloud base height are plotted in Fig. 2(a), where RCS is used as a background. The STRAT's best estimate of ABLH, as well as an additionally smoothed one, are presented along with the graph-processed candidates in Fig. 2(b), (RCS is the background). Sun and moon symbols mark sunrise and sunset, respectively. Obviously, the first graph (from 0:00 to 8:00 UTC) encompasses the nocturnal boundary layer and the early stages of the development of a new convective ABL. It takes few hours since sunrise for the earth's surface to be heated sufficiently, allowing the height of the new convective boundary layer to exceed the blind zone of the ceilometer. The strongest gradients observed between 1000 m and 1800 m are part of the residual layer and so they are not related to the convective ABL. Applying smoothing is not beneficial in that case. However, the graph-based method demonstrates reliable ABL tracing during this period. The second graph (spanning from 8:00 to 14:30 UTC) covers the intensive development of the convective ABL until it reaches its maximum height. All methods perform similarly. Lastly, the third graph (spanning from 14:30 to 24:00 UTC) covers the evening transition of convective to stable boundary layer. STRAT exhibits some noisiness after sunset, but the graph- and the smoothing-based methods are barely affected.

Although cloud-free days provide a classical development of ABL, the clouds occurrence as well as advected aerosol layers pose challenges for lidar-based ABL retrieval techniques.

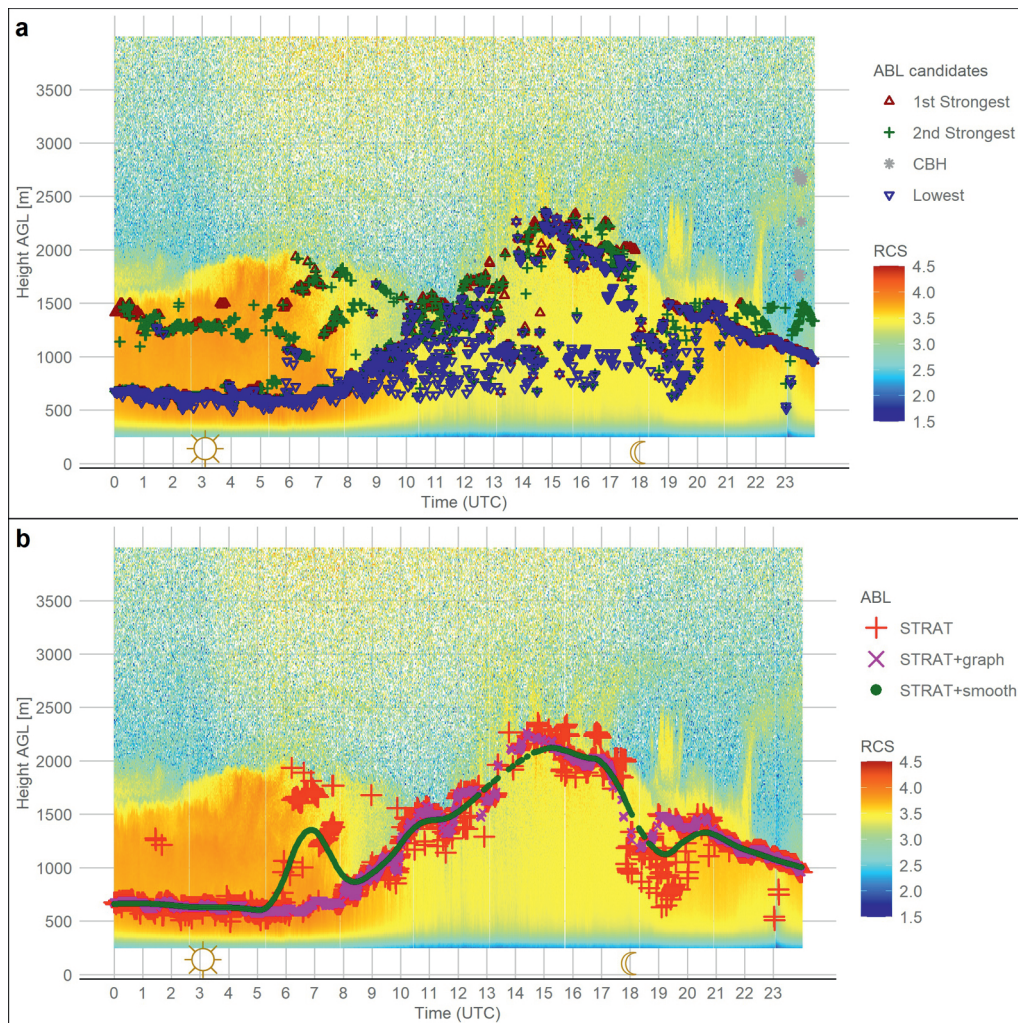


Fig. 2. Time-height plot of RCS recorded on July 22, 2015. Sun and moon symbols mark sunrise and sunset, respectively. STRAT's ABL candidates are shown in (a). STRAT's best estimates, along with the smoothed ones, and graph based ABLHs are shown in (b)

The second case study, depicted in Fig. 3, shows a cloud-topped atmospheric boundary layer (ABL) and an advected aerosol layer that is decoupled from the ABL, observed on July 7, 2015. The first graph accurately outlines the ABLH from 0:00 to 8:00 UTC, while the STRAT and its smoothed version are impacted by the aerosol layers aloft. The performance of the second graph is also notable, despite cumulus humilis formation around ABLH maximum (2300 m). The presence of a residual layer from 8:00 to 10:00 UTC causes difficulties for STRAT, but for the rest of the time, the daily dynamics of ABL is relatively accurate. After sunset, the evening transition is again causing problems for all algorithms.

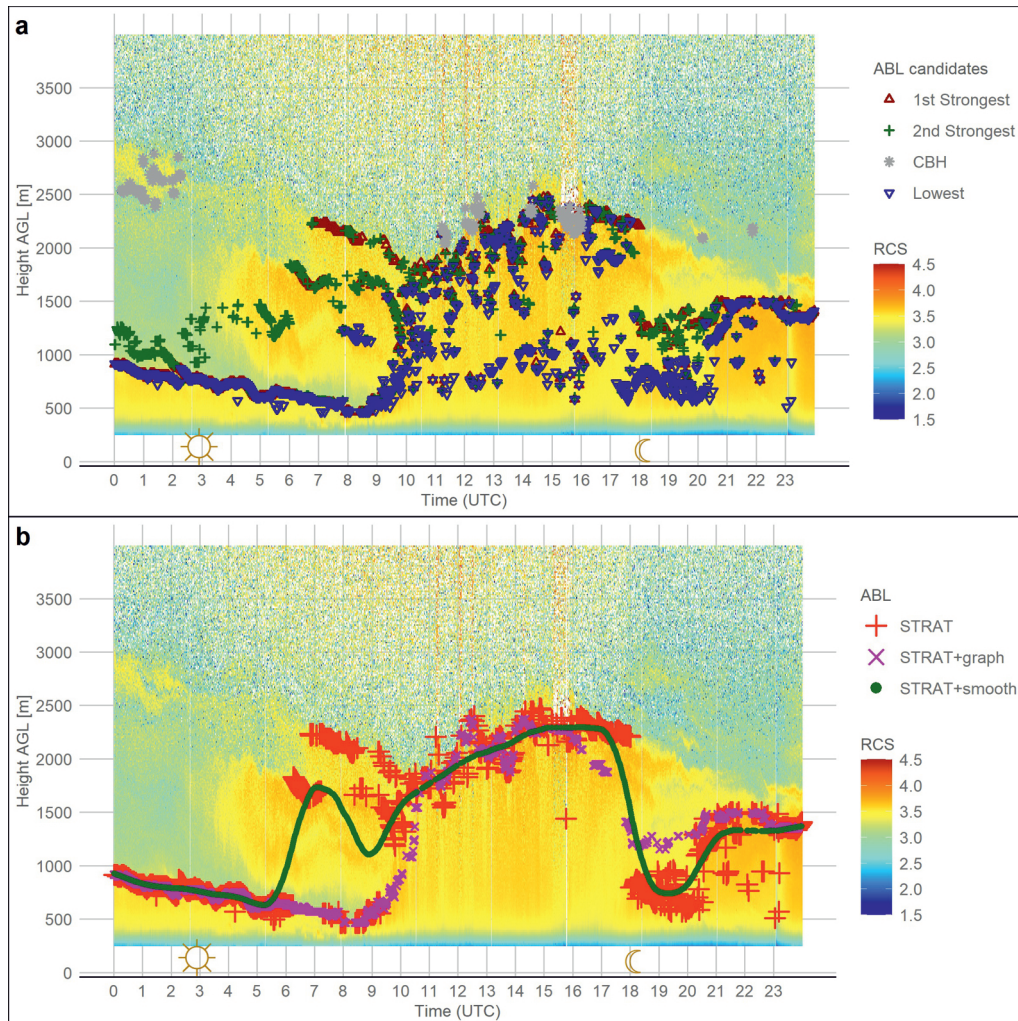


Fig. 3. Same as Fig. 2 but on July 7, 2015

Discussions. It is shown in two cases that the graph-based algorithm naturally restricts the search of ABLH in proximity to previous values, allowing it to demonstrate smooth, spike-free ABL tracing. However, the method's parameters may be sensitive to climate, location, and instrument specifics.

The selection of three graphs was imposed by the duration and start time of the data file since the ABL dynamics is governed by solar radiation and surface heating. If the data is arranged so that the first part covers the daytime evolution of the ABL and the second – the nighttime evolution (or vice versa), two graphs may be suitable. When the diurnal dynamics of ABL is barely noticeable, even one graph may be sufficient. However, using fewer graphs makes the calculations more

intensive and requires more computing time. Depending on the search window width and the growth rate parameter, the algorithm shows an ability to capture individual thermals in the ABL dynamics. When several possible pathways have close total lengths, increasing or decreasing the ABLH growth rate parameter may favour the outcome of one of these competing pathways. This would change the ABLH estimates and ABL consistency.

The smoothing approach is robust against a single outlier, but the presence of more may deteriorate the results of the algorithm. The existence of separate aerosol layers remains a serious challenge, resulting in mediocre performance.

The height of nocturnal boundary layer is hardly measured by the instrument, regardless of the algorithm, due to the incomplete overlap in the optical system within the first few hundred meters. Fogs and precipitation are another major issue for ABLH retrieval algorithms. During such events, large gradients in RCS are observed that may be incorrectly attributed to ABLH. The ABL detection is further hampered by the total attenuation of the ceilometer's signal during precipitation.

It should be noted that the determination of ABLH can be based on profiles of various variables (potential temperature, mixture ratio, concentrations of passive substances, wind profiles and turbulence characteristics, etc.) and their response to turbulent mixing in ABL and adaption to the dynamic equilibrium with the surface can vary. Therefore, different remote sensing instruments have their own advantages and limitations in ABLH retrieval [20]. Unfortunately, there is no other type of continuously operating collocated instrument in Sofia that can provide ABLH estimates for comparison.

Conclusions. The proposed graph-based approach operates as a post-processor over ABL candidates and manages to overcome possible fluctuations in ABLH dynamics that are inherent to algorithms processing a single lidar profile. The algorithm shows better ABL retrieval than non-parametric regression when compared against visually recognized diurnal ABL development in the RCS plot in two cases of fair-weather. Despite its advantages, the algorithm experiences some difficulties during the evening transition from convective to stable ABL. Like other algorithms, the proposed one also fails in ABLH retrieval from ceilometer data during precipitation, as well as in the absence of a distinct difference between the aerosol loading in the ABL and the free atmosphere.

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