

# AUTOMATIC MONITORING OF BOUNDARY LAYER STRUCTURES WITH CEILOMETER

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## ABSTRACT

Ceilometers are eye-safe, compact and robust lidar systems designed for unattended operation at airfields and meteorological stations. Their primary task is the detection of cloud base layers; automatic monitoring of boundary layer structures has become another important application of these instruments.

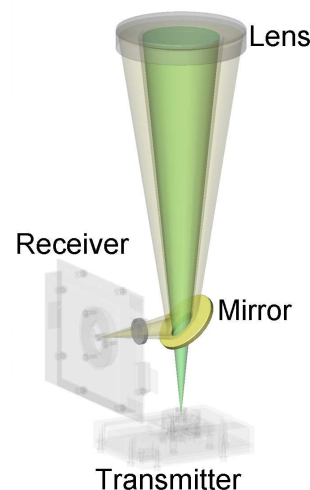
An automatic algorithm for online retrieval of boundary layer depth and additional residual structures has been developed that covers not only ideal boundary layer diurnal evolution, but all situations involving clouds, fog, and precipitation. This algorithm is part of the Vaisala boundary layer reporting and analysis tool BL-VIEW.

During a two years evaluation period, the U.S. National Weather Service permanently collected backscatter profiles from at least three Vaisala CL31 ceilometers at its test site in Sterling, VA. The automatic algorithm has been tested on this extensive database and on data from the Vaisala test sites in Vantaa, Finland, and Hamburg, Germany. Examples covering a variety of meteorological situations in all seasons are presented that demonstrate the quality of the algorithm and its application in the field of air quality forecasting.

## 1. Introduction

Eye-safe lidar ceilometers are reliable tools for unattended boundary layer structure monitoring around the clock up to heights exceeding 2500 m [1, 2]. Comparison to temperature, humidity, and wind profiles reported by RASS, sodar, radio soundings, and weather mast in-situ sensors has confirmed their ability to detect convective or residual layers [3]. In addition, ceilometers with a single lens optical design enable precise assessment of inversion layers and nocturnal stable layers below 200 m. This design has been chosen for the Vaisala Ceilometers CL31 and CL51 [5].

## 2. Instrumentation



**Figure 1.** Vaisala Ceilometers CL51 (left) and CL31 and their optical concept

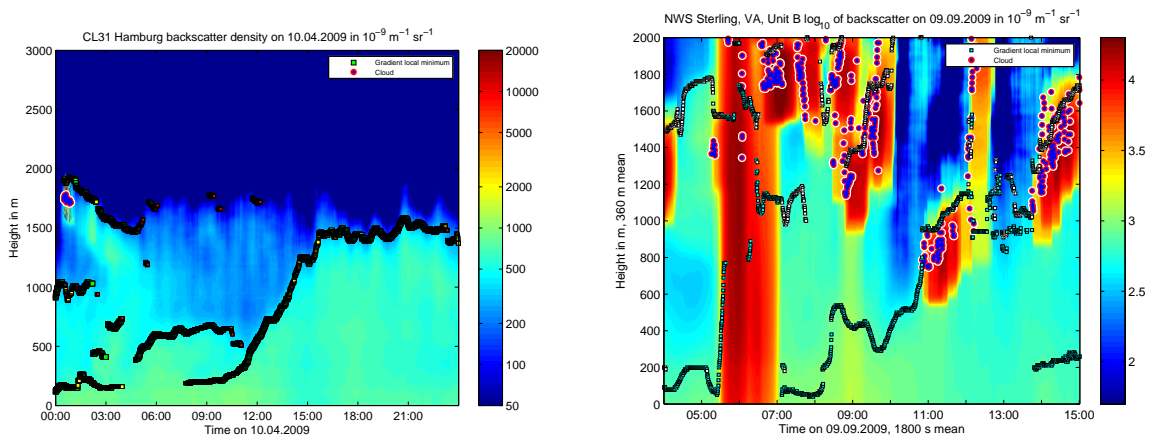
The single lens optical design of the Vaisala Ceilometers CL31 and CL51 uses the inner part of the lens for transmitting and its outer part for receiving light (Fig. 1). This provides overlap of the transmitter light cone and the receiver field-of-view over the whole measuring range and allows reliable detection of also the very low nocturnal stable layers below 200 m not seen by other instrument types. The main performance characteristics of the two instruments are listed in Table 1.

The CL31 ceilometer has been chosen as standard cloud height indicator for the Automated Surface Observing System of the U.S. National Weather Service (NWS); currently more than 2100 units are installed worldwide.

The CL51 ceilometer has a larger lens and a more powerful laser source to enable cloud base reports up to 13000 m. Its increased signal-to-noise ratio reveals also weak elevated aerosol layers.

**Table 1.** Performance characteristics of the Vaisala Ceilometers CL31 and CL51

	CL31	CL51
Minimum range resolution	5 m	10 m
Typical range resolution for boundary layer scans	10 m	10 m
Minimum report interval	2 s	6 s
Typical report interval for boundary layer scans	16 s	36 s
Measuring range for cloud base detection	0 ... 7500 m	0 ... 13000 m
Backscatter profile range	0 ... 7700 m	0 ... 15400 m
Range for boundary layer fine structure profiling	0 ... 4000 m	0 ... 4000 m
Total height	1190 mm	1531 mm
Total weight	31 kg	46 kg
Weight of measurement unit	12 kg	18.6 kg
Laser type	InGaAs diode	InGaAs diode
Laser wavelength	910 nm	910 nm
Eye-safety class	1M	1M



**Figure 2. Left:** Density plot (local time vs. height) of range corrected attenuated backscatter profiles recorded by a CL31 ceilometer at the Vaisala test site Hamburg, Germany, on April 10, 2009 with nocturnal, convective and residual layers.

**Right:** Density plot of range corrected attenuated backscatter profiles recorded by a CL31 ceilometer at the NWS test site Sterling, VA on September 9, 2009. Fixed sliding averaging parameters of 1800 s and 360 m are used that show a nocturnal and a convective layer. On this common day with rain and clouds, fixed averaging parameters do not reveal all aerosol layers in a satisfactory way.

### 3. Method

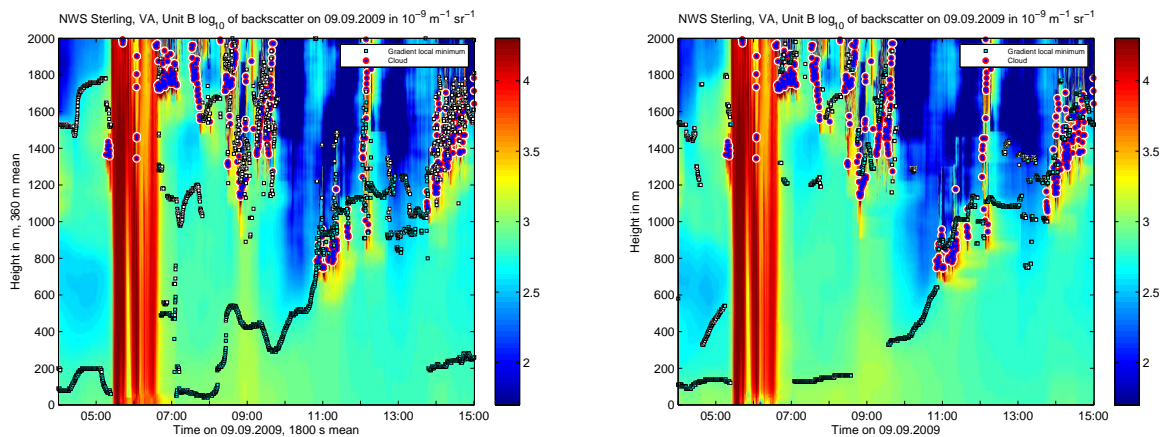
#### 3.1 Gradient method

A widely applied approach to identify the vertical extent of aerosol layers within the planetary boundary layer is the gradient method that searches the range and overlap corrected attenuated backscatter profile for local gradient minima [4]. Its application to ceilometer data involves averaging in time and range.

The CL31 recommended report interval for aerosol investigation is 16 s; profile range resolution is 10 m. Applying 1800 s and 360 m time and height sliding averaging reveals local gradient minima within the profiles and thus information about aerosol layers.

This approach works generally well for cloudless days (Fig. 2, left). In the right part of Fig. 2 backscatter profiles from a common day with rain and clouds are treated with the gradient method. A low nocturnal layer and a convective boundary layer evolving after about 10:00 local time are visible in this density plot. On the other hand precipitation and cloud bases call for a more sophisticated treatment. The following section describes the steps suggested to turn this standard gradient method into a robust algorithm that is able to identify situations when precipitation or fog prevents the detection of boundary layer height, and does not use high backscatter from preceding clouds for profile averaging.

#### 3.2 Enhanced robust algorithm



**Figure 3. Left:** Density plot of range corrected attenuated backscatter profiles recorded by a CL31 ceilometer at the NWS test site Sterling, VA on September 9, 2009. A cloud and precipitation filter is applied to the data shown in Fig. 2.

**Right:** Density plot of range corrected attenuated backscatter profiles recorded by a CL31 ceilometer at the NWS test site Sterling, VA on September 9, 2009. All steps of the novel robust algorithm for boundary layer investigation have been applied.

The first step towards a robust all weather algorithm is the application of a cloud and precipitation filter. In Fig. 2, the large backscatter values from the single 1300 m cloud at 09:40 are still visible half an hour later when no cloud was detected in that range. High back-scatter from clouds and precipitation should therefore not be used in the averaging process. The result of applying this filter is shown in Fig. 3 (left). It reveals that there was no more precipitation after 06:30 and allows a better view on aerosol backscatter from the vicinity of clouds. Reporting of gradient minima is not done during the precipitation event.

Long averaging intervals help preventing false gradient minima hits generated by signal noise. On the other hand, this approach reduces the ability of the algorithm to respond to short scale signal fluctuations in space and time. Signal noise amount is depending on range and time of the day. The enhanced auto-matic algorithm introduces variable averaging parameters that enable a much better view on a stable nocturnal layer at a height around 100 m that is detected before and after the morning rain shower (Fig. 3, right).

The final step towards the enhanced gradient method involves the suppression of false layer hits generated by small fluctuations of the backscatter signal intensity. This is the case around 07:00 at

heights between 400 m and 1000 m. Fig. 3 (right) shows a nocturnal layer followed by a convective layer with cloud formation reaching 1600 m in the afternoon.

## 4. Results

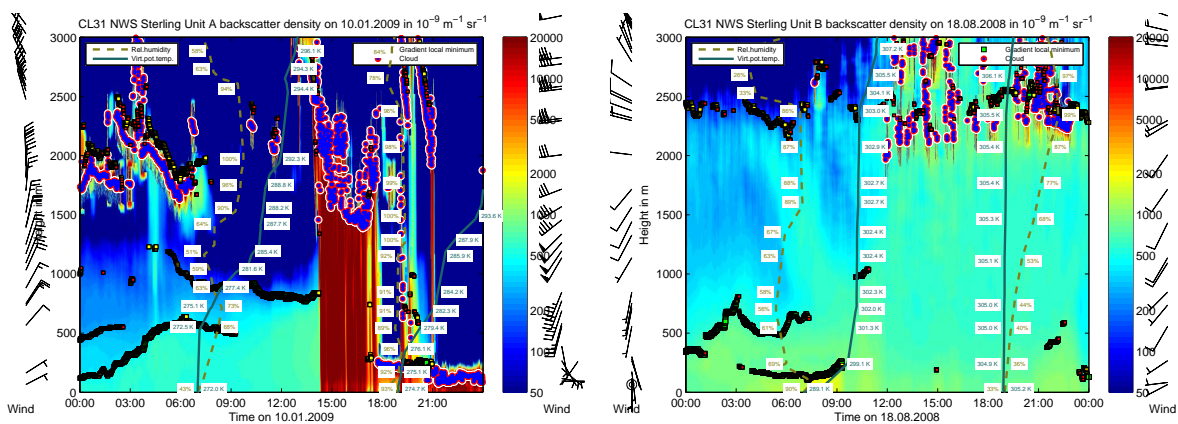
From the extensive CL31 database available from the NWS test site Sterling, a winter day with precipitation and low cloud layers, and a summer day with a high residual layer have been picked as examples.

A comparison between the two Vaisala Ceilometers CL31 and CL51 at Vantaa, Finland, shows the advantage of the improved signal-to-noise of the new CL51.

### 4.1 A winter day with clouds and precipitation

The first example (Fig. 4, left) shows data from January 10, 2009. A 100 m layer rises from 00:00 till 05:00 and stays at 500 m until 10:00 local time. Its altitude is confirmed by the 07:00 Sterling radio sounding that shows a virtual potential temperature rise at that altitude.

Rain showers start at 14:30; there are no more layer reports until 19:00. The virtual potential temperature profile at that time confirms a 250 m boundary layer reported by the automatic algorithm.



**Figure 4. Left:** Density plot of range corrected attenuated backscatter profiles recorded by a CL31 ceilometer at the NWS test site Sterling, VA on January 10, 2009. The automatic algorithm extracts all layer information from the profiles and suppresses reporting of gradient minima during the precipitation event starting at 14:00 local time. Radiosonde data from a co-located launch site are available twice daily at 07:00 and 19:00. Solid lines with attached numbers show the virtual potential temperature profiles, dashed lines give relative humidity. Wind barbs are plotted left of the density plot for the 07:00 sounding and right of it for the 19:00 sounding.

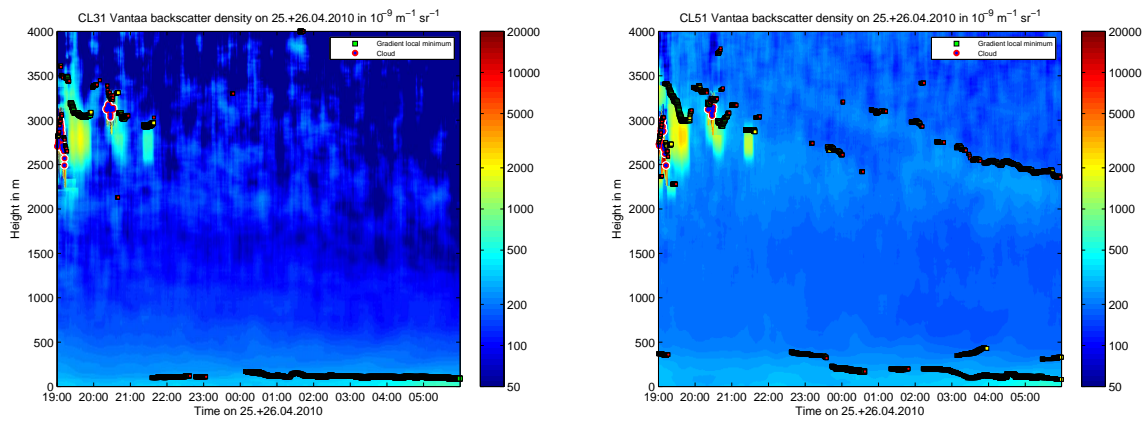
**Right:** Density plot of range corrected attenuated backscatter profiles recorded by a CL31 ceilometer at the NWS test site Sterling, VA on August 18, 2008 (see text for details).

### 4.2 A summer day with a high residual layer

On August 18, 2008, a uniform aerosol layer reaching up to 2500 m dominates all other layer evolution on that day (Fig. 4, right). This high layer is confirmed by the soundings showing virtual potential temperature rises and relative humidity drops at that height. The nocturnal layer forming at 03:00 is also confirmed by sounding data.

### 4.3 CL31 and CL51

The advantage of the increased signal-to-noise ratio of the CL51 ceilometer is demonstrated in Fig. 5. An elevated layer between 2000 m and 3000 m is hardly recognizable in the CL31 profiles, but is reported by the CL51.



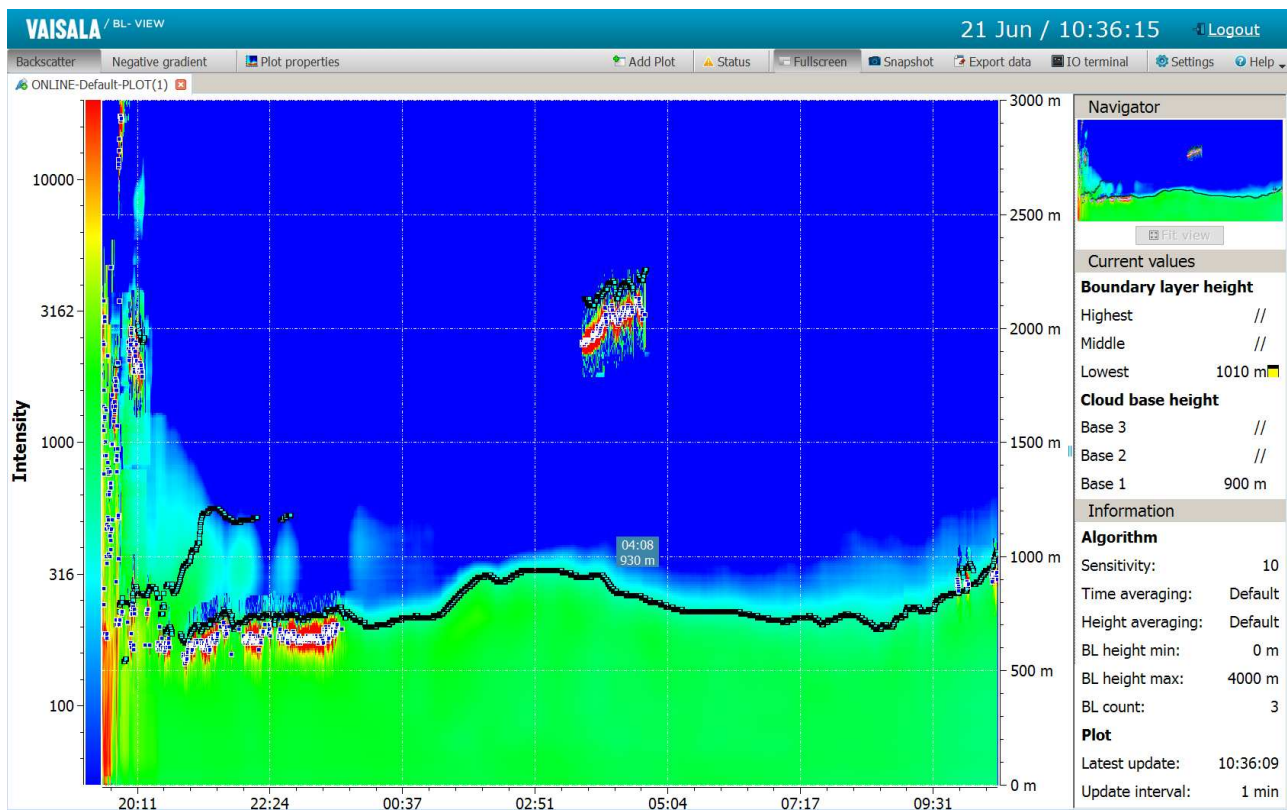
**Figure 5.** Density plots of range corrected attenuated backscatter profiles recorded by a CL31(left) and a CL51 ceilometer at the Vaisala test site Vantaa, Finland.

## 5. BL-VIEW

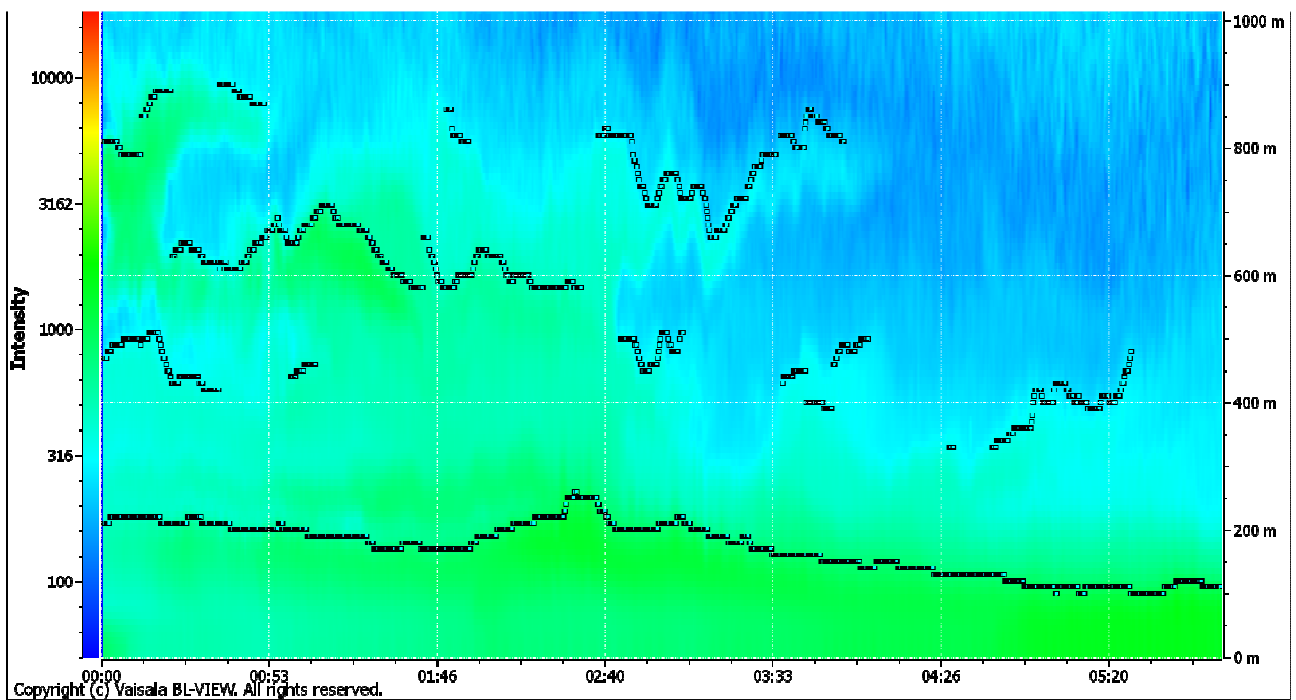
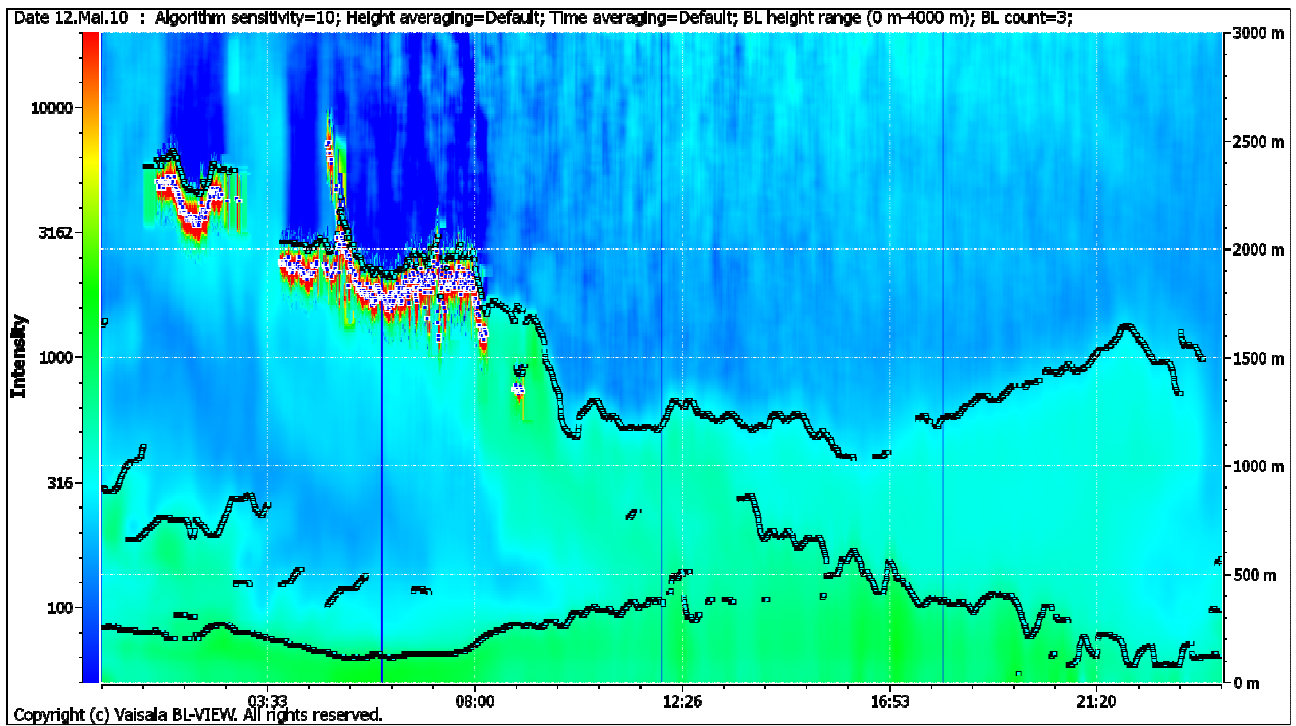
In July 2010, Vaisala has launched its planetary boundary layer reporting and analysis tool BL-VIEW, a PC-software package designed as a support and decision tool for air quality monitoring, research and wind energy applications.

Fig. 6 shows the default online view of BL-VIEW (CL31 in Hamburg, Germany), Fig. 7 gives offline views from a spring day (CL51 in Vantaa, Finland).

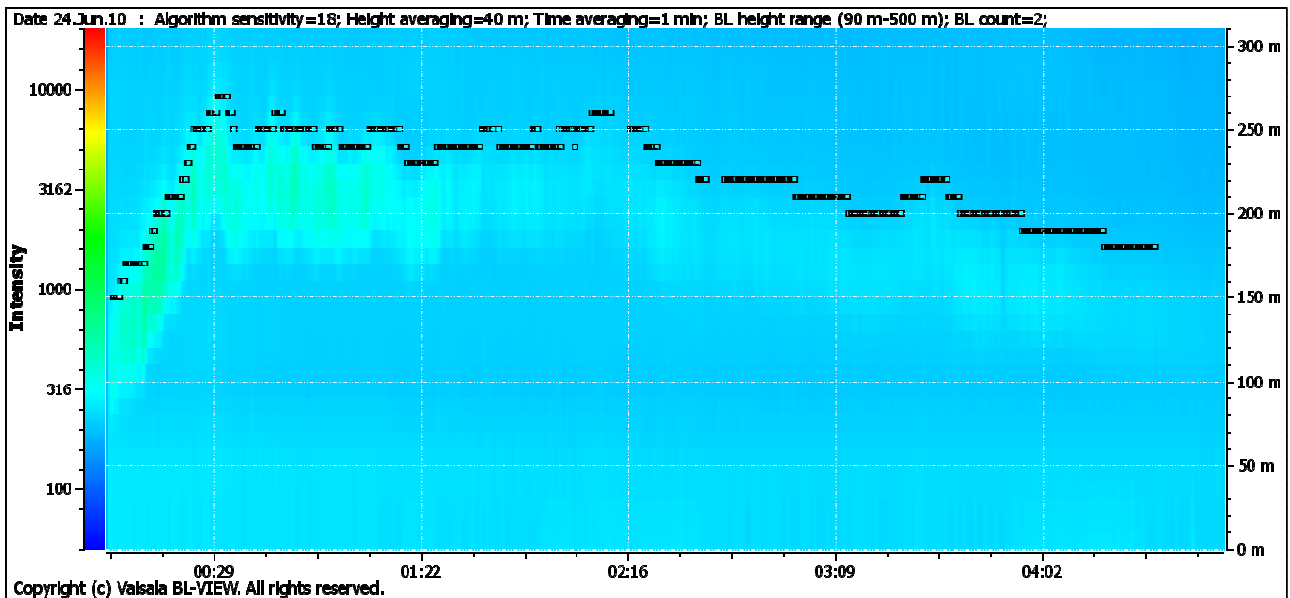
The advantage of full overlap in the very near range is demonstrated by the precise monitoring of a low weak plume over Vantaa, Finland (Fig. 8).



**Figure 6.** BL-VIEW online view with current boundary layer and cloud base heights and density plots (June 21, 2010, Hamburg, Germany)



**Figure 7.** BL-VIEW snapshots of backscatter profiles collected on May 12, 2010, in Vantaa, Finland. The upper part shows rendering with default settings, the lower part is a blow up of fine structures during the night hours of that day; averaging parameters have been changed to 40 m and 60 s to reveal more details of weak structures (backscatter intensity  $< 500 \cdot 10^{-9} \text{ m}^{-1} \text{ sr}^{-1}$ ) within the boundary layer.



**Figure 8.** BL-VIEW snapshot of backscatter profiles collected on June 24, 2010, in Vantaa, Finland, showing a weak plume (backscatter intensity  $< 10^6 \text{ m}^{-1} \text{ sr}^{-1}$ ). This example demonstrates the advantages of the one lens optical concept and the high signal-to-noise ratio of the CL51 ceilometer.

## 6. Conclusions

Applying the enhanced gradient method introduced in this paper to a large variety of ceilometer profiles has confirmed its applicability for automatic boundary layer structure investigation.

It has been integrated in the planetary boundary layer reporting and analysis tool Vaisala BL-VIEW. This supportive PC-software package is designed as a support and decision tool for air quality monitoring, research and wind energy applications.

## 7. Acknowledgments

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