Boundary layer and air quality monitoring with a commercial lidar ceilometer

Christoph Münkel

Providing small, low-cost lidar systems with novel optical design and flexible electronics sharpens the view of particles in the lower troposphere, and enables new environmental monitoring applications.
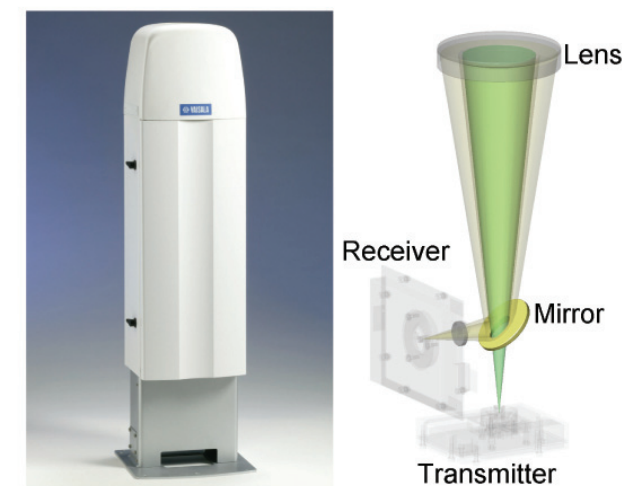
Lidar (light detection and ranging) remote sensing has enormous potential in atmospheric research and air quality monitoring,[1] made possible by the portion of emitted laser light that is scattered back to the instrument by particles in the atmosphere. The recorded backscatter profiles could be used, for example, to estimate the mixing layer's aerosol density and thickness, or mixing height (MH). Substances introduced into the mixing layer become completely mixed by turbulence given sufficient time.

These estimates would be useful in helping comply with European air quality framework directive 96/62/EC, which requires precise monitoring of pollution loading. The loading can be estimated using aerosol optical thicknesses retrieved from satellite-based observations,[2] together with the MH.

High costs, scarcity, and eye-safety considerations exclude research lidar systems as a candidate for a dense MH retrieval network. I show here that eye-safe lidar ceilometers of the sort used to report cloud base heights at most airfields can, with modest modifications introduced by Vaisala GmbH, provide a cost-effective alternative.

The traditional ceilometer concentrates on cloud base detection using either a two-lens or a one-lens approach. The two-lens design provides little or no laser beam and receiver field-of-view overlap for collecting aerosol backscatter in the near range up to 100m, a crucial range for air quality applications.

The single-lens design, which uses the same lens for transmitting and receiving, provides full overlap over the whole measuring range, but requires compensating mechanisms to prevent receiver saturation from direct lens reflections that lower data quality in the near range. Poor range resolution, low pulse rep-
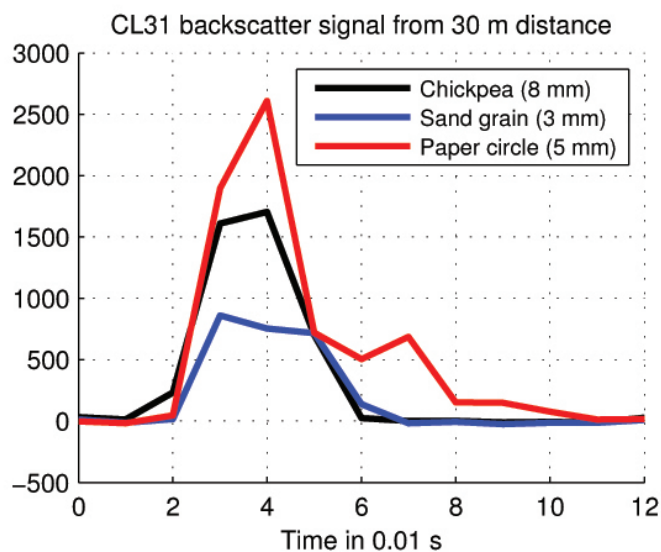

Figure 1. *Shown is the Vaisala Ceilometer CL31 and a schematic drawing of its optical concept. A hole in the mirror divides the lens into an inner part used by the transmitter and an outer ring visible to the receiver.*

etition frequency, and long minimum report interval further decrease the performance of standard ceilometers.

The shortcomings of both designs are overcome by the novel optical design of the Vaisala Ceilometer CL31, shown in Figure 1. This instrument incorporates the advantages of both optical concepts, and the disadvantages of neither. Its fast electronics make it an all-purpose backscatter lidar, fit for standard ceilometer tasks and air quality applications.[3]

The right part of Figure 1 shows the enhanced single-lens design for the CL31. We use the center of the lens for collimating the outgoing laser beam, and the outer part to focus the backscattered light onto the receiver. This division between transmitting and receiving areas is provided by an inclined mirror with a hole

The International Society
for Optical Engineering

Figure 2. The basic monitoring capabilities of the enhanced ceilometer are shown using various targets. A paper circle stays longer in the laser beam than the faster moving objects. A chickpea gives a larger return signal than the smaller sand grain.
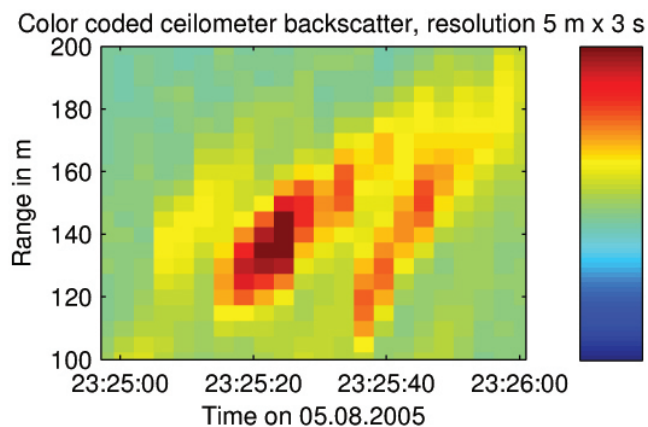
Figure 3. The backscatter density plot of spray drifting away from the ceilometer is shown. The high resolution of the measurement allows an estimation of the wind speed.

in the center. The arrangement makes the receiver practically blind to light reflected by the lens, but still provides sufficient overlap as close as a 5m range. A digital signal processor with a clock frequency of 60MHz manages both data sampling and calculation tasks, using a standard pulse repetition rate of 10kHz. The layout of the embedded software allows switching between multiple data acquisition modes. The minimum backscatter profile resolution is 5m in range and 2s in time, and can make mea-
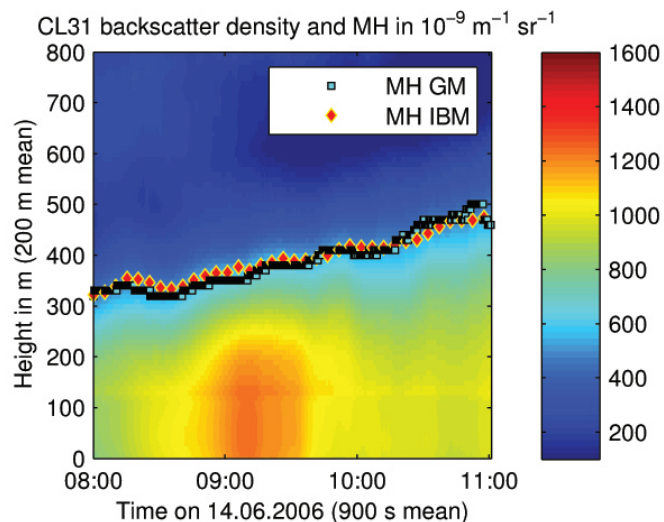
Figure 4. A convective boundary layer with gradually rising mixing height (MH) values is shown evolving in the morning hours of a summer day. The MH estimates based on the gradient method (GM) and the idealized backscatter method (IBM) are in good accord.

surements out to 7700m. For special applications with a reduced measuring range, profile report frequencies of 100Hz or more can be achieved.

To demonstrate this fast measurement mode, we used the 100Hz report frequency and dropped particles of different sizes and shapes into the laser beam of a CL31 ceilometer measuring in a nearly horizontal direction. Figure 2 shows the result. Possible applications in this case are remote detection of falling hailstones and discrimination between different kinds of precipitation.

The same measurement setup has been used for comparison between ceilometer backscatter, atmospheric extinction reported by a transmissometer, and concentration of particulate matter smaller than $10\mu m$ (PM10) measured by an in situ instrument. At visibilities between 5 and 30km, I have found good correlation between backscatter and extinction values and confirmation of the ability of a ceilometer to estimate PM10 concentration values.[4,5]

Left unattended to run continuously for about a year in an industrial area, the CL31 reported many different events in its horizontal measuring path, including dust and smoke plumes from a nearby asphalt plant, and traces of a New Year firework rocket launched 1km away. Figure 3 shows a quite exotic application: reflections from spray caused by single vehicles after a rain shower imply that the wind speed in the measuring direction of the ceilometer is around 4m/s. This is well correlated to values reported by a nearby wind sensor.

Figure 4 demonstrates the instrument's chief air quality application, the detection of mixing height. The figure shows MH determination using two methods. The gradient method (GM) looks for the steepest descent in the averaged backscatter profiles, while the more sophisticated 'idealized backscatter' method (IBM) fits measured profiles to an ideal profile with constant backscatter values within the mixed layer.[6] The two results are in general agreement.

Various measuring campaigns carried out by research institutes and environmental agencies around the globe show that its enhanced single-lens concept and fast electronics make the ceilometer CL31 a reliable tool for mixing height assessment. Low acquisition and maintenance costs make it an ideal candidate for a required network. Our next step will be to improve the robustness of the retrieval algorithms when aerosol density is low, and in the presence of clouds or precipitation.

Author Information

Christoph Münkel
Vaisala GmbH
Hamburg, Germany
http://www.vaisala.com/businessareas/instruments
/products/cloudheight

Christoph Münkel is working as a scientist in the optical sensors research department of Vaisala. Previous postings were at Hamburg University and at Helmut Schmidt University in Hamburg. He received his MS degree in mathematics from Hamburg University in 1978. Münkel presented his first paper at a SPIE symposium in 1995. He is a regular author for the conference Remote Sensing of Clouds and the Atmosphere, for which he chaired a session in 2006.

References

1. C. Weitkamp ed., **Lidar: range-resolved optical remote sensing of the atmosphere**, Springer, New York, ISBN 0-387-40075-3, 2005.
2. N. Sifakis, N. Soulakellis, and D. Paronis, *Quantitative mapping of air pollution density using Earth observations: a new processing method and application to an urban area*, **Intern. J. Rem. Sens. 19** (17), pp. 3289–3300, 1998.
3. C. Münkel and J. Räsänen, *New optical concept for commercial lidar ceilometers scanning the boundary layer*, **Proc. SPIE 5571**, pp. 364–374, 2004. doi:10.1117/12.565540
4. C. Münkel, S. Emeis, W. J. Müller, and K. Schäfer, *Aerosol concentration measurements with a lidar ceilometer: results of a one year measuring campaign*, **Proc. SPIE 5235**, pp. 486–496, 2004. doi:10.1117/12.511104
5. C. Münkel, *Boundary layer and air quality monitoring with a commercial lidar ceilometer*, **Proc. SPIE 6367**, 2006. doi:10.1117/12.689775
6. N. Eresmaa, A. Karppinen, S. M. Joffre, J. Räsänen, and H. Talvitie, *Mixing height determination by ceilometer*, **Atmos. Chem. Phys. Discuss 5**, pp. 12697–12722, 2005.