The cloud base is just the beginning:
Advanced applications of Vaisala ceilometers

Christoph Münkel, Vaisala GmbH, Hamburg, Germany
Contents

- Introduction to Vaisala ceilometers
- Ceilometer calibration
- Monitoring particle emissions
- Elevated dust layers
- Extinction profiles
- Mixing layer height determination
- High resolution profiling
Single lens ceilometer Vaisala CL31

- Simple and reliable instrument design.
- Sufficient overlap already 10 m above the system.
- More than 4000 units in operation.
Single lens ceilometer Vaisala CL51

- Unchanged optical setup compared to CL31.
- Larger lens and modified electronics increase SNR significantly.
- Qualified instrument for boundary layer investigation.
- Designed for harsh environments.
16384 laser pulses are accumulated within 2 s for a single reported profile.

No problem for the cloud base detection algorithm.

Speed of light: $300 \times 10^6$ m/s = 300 m/µs

There and back: $2 \times 1500$ m in 10 µs
A typical CL51 backscatter profile density plot

- **Cloud**
- **Nocturnal layer**
- **Melting layer**
- **Residual layer**
- **Precipitation**
Hot topic in the scientific community – calibration of ceilometers

TOPROF (COST Action ES1303)
Towards operational ground based profiling with ceilometers, doppler lidars and microwave radiometers for improving weather forecasts

- WG 1 of TOPROF is investigating the following methods:
  - Rayleigh Calibration
  - Cloud calibration
  - Reference Lidar (not operational)
- Vaisala ceilometers are factory calibrated.
- During operation the calibration factor is maintained by monitoring laser power and window transmission.
Are results from different ceilometers comparable? A random investigation of four co-located CL31 ceilometers

- Before purchasing 1000 CL31 ceilometers, the US National Weather Service did extensive testing.
- For more than two years, up to five co-located ceilometers were operated in a circle with a diameter of 30 m.
- The following slides show 25 minutes with a rather stable 3700 m cloud base.
- Signal integral over the whole measuring range should not differ significantly.
- On the randomly chosen time 2008-07-02 00:54:00, the average signal integral of the four units was 0.0152 sr\(^{-1}\) with a standard deviation of 0.00059 sr\(^{-1}\) corresponding to 3.9 %. 

Some thoughts about Rayleigh calibration

- Rayleigh calibration method requires ceilometer data from a very clear night, averaged over several hours.
- It tries to identify regions within the attenuated backscatter profile that are practically aerosol free.
- But how can we be sure that we chose the right region?
- The following examples show that there is very often something up there that a ceilometer has difficulties to see.
- Consequently Vaisala favours the cloud calibration method introduced by Ewan O‘Connor.

http://www.met.reading.ac.uk/~swr99ejo/publications/lidar_calibration.pdf
HSRL at Hyytiälä – a powerful lidar reveals a lot of elevated aerosol layers
CL51 at Hyytiälä – HSRL structures are barely visible

CL51 attenuated backscatter in m$^{-1}$ sr$^{-1}$ on 17-May-2014, averaging: 40 min / 360 m
HSRL at Hyytiälä – a powerful lidar reveals a lot of elevated aerosol layers
CL51 at Hyytiälä – HSRL structures are barely visible

CL51 attenuated backscatter in m⁻¹ sr⁻¹ on 11-Jul-2014, averaging: 40 min / 360 m
Monitoring particle emissions

A classical lidar application: Backscatter signal peaks hint on increased particle concentration.
Monitoring particle emissions

CL51 Station Nord attenuated backscatter in m$^{-1}$ sr$^{-1}$ (60 s * 10 m)

Ceilometers register ice crystals aloft. Monitoring these events helps to understand the process of arctic cloud formation.
Elevated dust and ash layers

Dust layer from Gobi Desert

Source: at 39.93 N, 116.28 E

Meters AGL

Beijing

Mongolia

NOAA HYSPLIT MODEL
Backward trajectory ending at 1100 UTC 17 Apr 13
GDAS Meteorological Data

Dissipated backscatter density plot (96 s * 40 m)

Job ID: 13815
Job Start: Mon Jul 29 11:25:56 UTC 2013
Source 1 lat.: 39.93 lon.: 116.28 height: 3500 m AGL
Trajectory Direction: Backward Duration: 36 hrs
Vertical Motion Calculation Method: Model Vertical Velocity
Meteorology: 0000Z 15 Apr 2013 - GDAS1

Date (8 h ahead of UTC) on 17.04.2013
Extinction profiles

\[
P(x, \lambda) = \frac{c}{2x^2} P_0 A \eta O(x) \Delta t \frac{\beta(x, \lambda) \tau^2(x, \lambda)}{\text{instrument specific} \quad \text{attenuated backscatter}}
\]

\[
\tau(x, \lambda) = \exp \left[ - \int_0^x \alpha(\xi, \lambda) d\xi \right]
\]

- Ceilometers report the attenuated backscatter part of the simplified lidar equation.
- According to ISO 28902-1 (ground-based remote sensing of visual range by lidar), profiles of the extinction coefficient \( \alpha \) can be derived from this if
  - \( \alpha \geq 0.0015 \text{ m}^{-1} \) (corresponding to \( \text{MOR} \leq 2000 \text{ m} \)),
  - a linear and range-independent relation of \( \alpha \) and \( \beta \) is assumed.
- These assumptions are fulfilled to a high extent during haze events in megacities.
A haze event in Beijing – attenuated backscatter

CL51 C Beijing attenuated backscatter in m⁻¹ sr⁻¹ (48 s * 20 m)

Cleaning the window increases attenuated backscatter

Local time (8 h ahead of UTC) on 06.05.2013
A haze event in Beijing – extinction profiles increase information content

- Attenuated backscatter too low for application of Klett-Fernald algorithm.
- Cleaning the window does not affect extinction.
- Formation of a dense haze layer only visible in extinction profiles.

Beijing extinction coefficient in m$^{-1}$ (48 s * 20 m)
Ground extinction coefficient verification with MOR

- There are various CL51 installations with attached visibility meter reporting MOR (meteorological optical range).
- These values could be used to verify the validity of the assumptions made for the derivation of extinction profiles.
Extinction coefficient verification with forward scatter visibility meter PWD52
Mixing layer height determination

CL51 ZAMG Attenuated Backscatter Density on 01.08.2012 in $10^{-9} \text{ m}^{-1} \text{ sr}^{-1}$

Height in m, 60 - 240 m mean

Time, 0830 - 2030 s mean

Gradient local minimum
Cloud

26 MUE 3 [2020 2000]
MB 200 S 10 CC 1 HI 10
Negative gradient plot

CL51 ZAMG Negative Gradient on 01.08.2012
Pick gradient minima as layer tops
BL-VIEW algorithm reports up to 3 layers
BL-VIEW algorithm reports up to 3 layers

Presentation with the Vaisala SW product BL-VIEW
Radiosondes confirm layer tops

CL51 ZAMG Attenuated Backscatter Density on 01.08.2012 in 10^{-9} \text{ m}^{-1} \text{ sr}^{-1}
High res plot shows the good near-range behavior
A CL51 with BL-VIEW is running in the Finnish Embassy in Beijing
Two co-located CL51 ceilometers at Hamburg Wettermast

<table>
<thead>
<tr>
<th></th>
<th>Standard mode</th>
<th>High res mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRF</td>
<td>8.192 kHz</td>
<td>8.192 kHz</td>
</tr>
<tr>
<td>Range resolution</td>
<td>10 m</td>
<td>10 m</td>
</tr>
<tr>
<td>Measuring range</td>
<td>7700 m</td>
<td>1800 m</td>
</tr>
<tr>
<td>Profile report interval</td>
<td>16 s</td>
<td><strong>0.5 s</strong></td>
</tr>
</tbody>
</table>
Investigation of rising and falling aerosol plumes with high res mode
This cooled bubble falls 120 m in 60 s
Acknowledgements

- Many thanks to these institutions and individuals that helped providing data and photographs for this presentation
  - Sven-Erik Gryning, Rogier Floors
  - Martin Piringer, Christoph Lotteraner, Erwin Petz
  - Fabian Eder, Matthias Mauder
<table>
<thead>
<tr>
<th></th>
<th>CL31</th>
<th>CL51</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum range resolution</td>
<td>5 m</td>
<td>10 m</td>
</tr>
<tr>
<td>Typical range resolution for boundary layer scans</td>
<td>10 m</td>
<td>10 m</td>
</tr>
<tr>
<td>Minimum report interval</td>
<td>2 s</td>
<td>6 s</td>
</tr>
<tr>
<td>Typical report interval for boundary layer scans</td>
<td>16 s</td>
<td>36 s</td>
</tr>
<tr>
<td>Measuring range for cloud base detection</td>
<td>0 … 7500 m</td>
<td>0 … 13000 m</td>
</tr>
<tr>
<td>Backscatter profile range</td>
<td>0 … 7700 m</td>
<td>0 … 15400 m</td>
</tr>
<tr>
<td>Range for boundary layer fine structure profiling</td>
<td>0 … 4000 m</td>
<td>0 … 4000 m</td>
</tr>
<tr>
<td>Total height</td>
<td>1190 mm</td>
<td>1531 mm</td>
</tr>
<tr>
<td>Total weight</td>
<td>31 kg</td>
<td>46 kg</td>
</tr>
<tr>
<td>Weight of measurement unit</td>
<td>12 kg</td>
<td>18.6 kg</td>
</tr>
<tr>
<td>Laser type</td>
<td>InGaAs diode</td>
<td>InGaAs diode</td>
</tr>
<tr>
<td>Laser wavelength</td>
<td>910 nm</td>
<td>910 nm</td>
</tr>
<tr>
<td>Eye-safety class</td>
<td>1M</td>
<td>1M</td>
</tr>
</tbody>
</table>
Ash from the Puyehue-cordon-caulle eruption monitored over Antarctica
NOAA HYSPLIT backward trajectories confirm volcanic ash cloud detection

Puyehue-cordon-caulle
Arctic ice crystals aloft

NOAA HYSPLIT MODEL
Backward trajectory ending at 0400 UTC 30 Oct 11
GDAS Meteorological Data

CL51 Station Nord attenuated backscatter density plot (4 min * 80 m)

Source ★ at 81.60 N 16.67 W
Meters AGL
1800 ★ 2500 2000 1500 1000 500

Job ID: 15445   Job Start: Mon Aug 26 08:11:56 UTC 2013
Source: 1   lat.: 81.600000   lon.: -16.670000   height: 1800 m AGL
Trajectory Direction: Backward   Duration: 96 hrs
Vertical Motion Calculation Method: Model Vertical Velocity
Meteorology: 0000Z 29 Oct 2011 - GDAS1
Arctic ice crystals aloft

CL51 Station Nord attenuated backscatter density plot (4 min * 80 m)