VAISALA

WHITE PAPER

# Applications for Vaisala Lidar Ceilometer CL61 with depolarization

# Applications for Vaisala Lidar Ceilometer CL61 with depolarization

## Table of Contents




*Trusted weather observations for a sustainable future*

# 1 Introduction

Ceilometers are robust and cost-effective lidar-based remote sensing instruments. In addition to their traditional use in detecting cloud base heights in aviation, ceilometers are increasingly used for vertical atmospheric profiling for several applications. Attenuated backscatter profiles are used for cloud, boundary-layer, and elevated aerosol layer profiling. Further addition of depolarization ratio profiling allows straightforward identification of liquid and ice clouds, precipitation type, and melting layer, as well as improved potential for monitoring aerosols, smoke, dust, and volcanic ash. High-end profiling ceilometers can be operated unattended in networks to provide highly detailed atmospheric information.

Vaisala Ceilometer CL61 with depolarization measurement is a powerful profiling ceilometer. The chapters in this document focus on a wide range of applications for CL61, using figures and case study summaries to illustrate how to distinguish various features from attenuated backscatter and depolarization ratio profiles. With CL61, Vaisala is setting a new standard in high-end ceilometer analysis and applications.


# 2 Attenuated backscatter and depolarization ratio

## Attenuated backscatter measurement

The emitted laser pulse is scattered by each particle it encounters on its path through the atmosphere. A portion of this light is scattered back towards the ceilometer and is registered. The rest of the light is either absorbed or scattered in directions not seen by the ceilometer. The portion of backscattered light registered is called attenuated backscatter.

The signal strength and shape in attenuated backscatter profiles contain a lot of information on the atmosphere. For example, a liquid cloud layer would show a strong peak and the signal would attenuate rapidly inside the cloud. For ice clouds the attenuated backscatter signal is relatively strong, however, the measurement signal is not attenuating in the cloud. The difference between the signal strength and attenuation is due to the size and number concentration of the particles in each cloud – ice cloud containing larger but fewer ice crystals and liquid cloud containing large amount of small liquid droplets.

Based on the attenuated backscatter it is possible to distinguish several features, such as:

- Liquid cloud
- Ice cloud
- Precipitation
- Fog
- Boundary layer characteristics
- Elevated aerosol layers
- Melting layer (in precipitation)

## Depolarization ratio measurement

Each particle interacts with the laser pulse by either maintaining or altering the polarization of the emitted light. CL61 with depolarization measures these changes in polarization, and reports them as profiles called the linear depolarization ratio, derived from parallel and perpendicular (to the transmitted light) components. Depolarization adds more clarity and reveal many features that would be difficult or impossible to distinguish by only using attenuated backscatter. For example, liquid and solid precipitation particles would not be distinguishable alone with attenuated backscatter but can be distinguished with linear depolarization ratio measurements. Ice clouds and liquid clouds show different characteristics when looking into depolarization effects: ice crystals are causing detection of depolarized signal as the transmitted light encounter multiple internal reflections when facing an ice crystal. In turn, spherical liquid droplets are not causing depolarized received signal and therefore the depolarization ratio for liquid cloud is close to zero.

Depolarization ratio profiles allow straightforward identification of several atmospheric features. The features already mentioned (cloud phase, liquid vs. solid precipitation, fog, melting layer) become quickly and confidently recognizable with side-by-side visual inspection with the attenuated backscatter profile. Lidars operating in one wavelength, such as CL61, cannot provide independent, unambiguous aerosol type identification. However, aerosol characterization is also possible, especially when additional information is available, such as other weather data, model backward trajectories, or complimentary research lidar measurements. CL61 with depolarization can be used more effectively for detecting:

- Supercooled liquid clouds
- Icing and freezing conditions
- Mixing layer height
- Dust / sand
- Volcanic ash
- Forest fire smoke

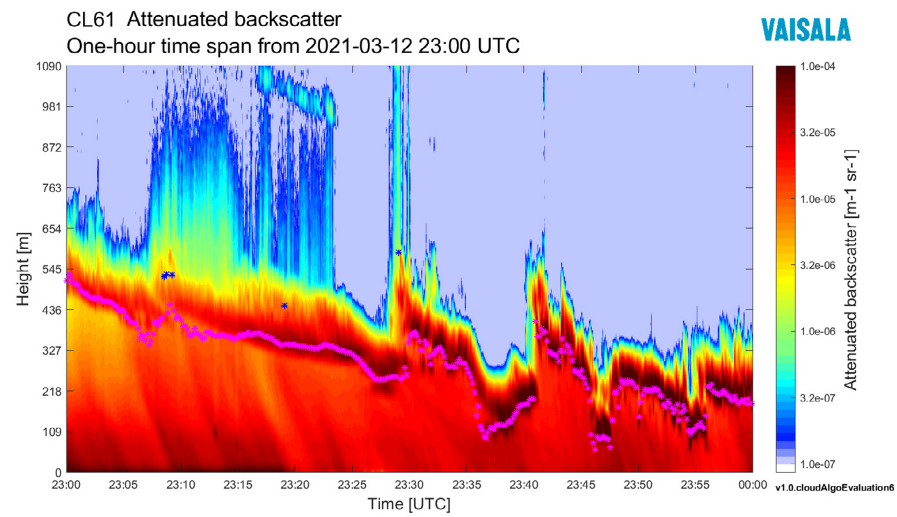
CL61 also reports parallel and perpendicular signal components separately, allowing further possibilities for inspecting atmospheric features, and flexible time averaging for depolarization ratio profiles.

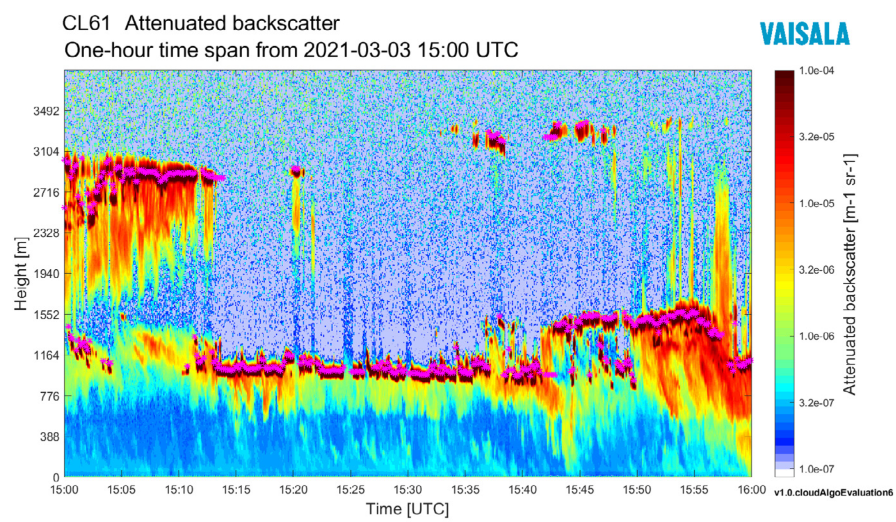
*Illustrative example only*

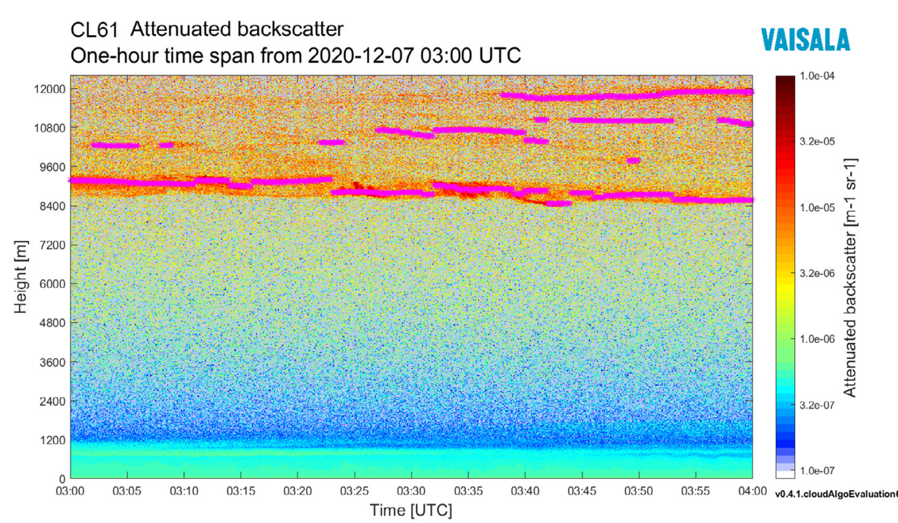
# 3 Standard ceilometer products

CL61 reports standard ceilometer products containing cloud base heights, vertical visibility and sky condition (cloud amount in okta) values. In addition to standard ceilo products, the attenuated backscatter profile, is also measured and stored, similarly to previous Vaisala ceilometer models CL31 and CL51. The cloud base heights are reported maximum at 5 levels at a time and CL61 is capable detecting low-, mid- and high-level clouds. In case the cloud base is not visible, the CL61 reports vertical visibility, similarly to previous Vaisala ceilometers.

In the following figures, x-axes represent the time in UTC and y-axes represent the height in meters. Magenta dots represent the cloud base and blue dots represent the vertical visibility. The example cases are measured at Vaisala testfield in Finland, and represent low level clouds with precipitation, mid-level clouds and multiple layers of high clouds, correspondingly.



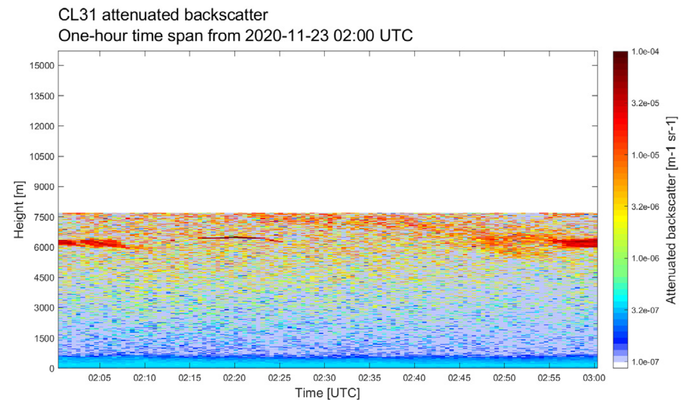



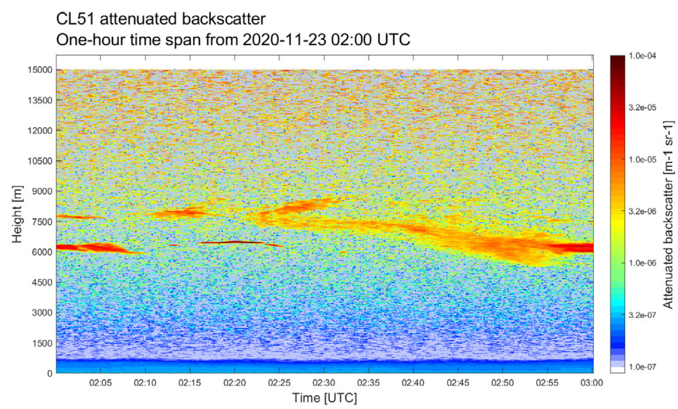
# 4 Evolution of Vaisala ceilometer product family

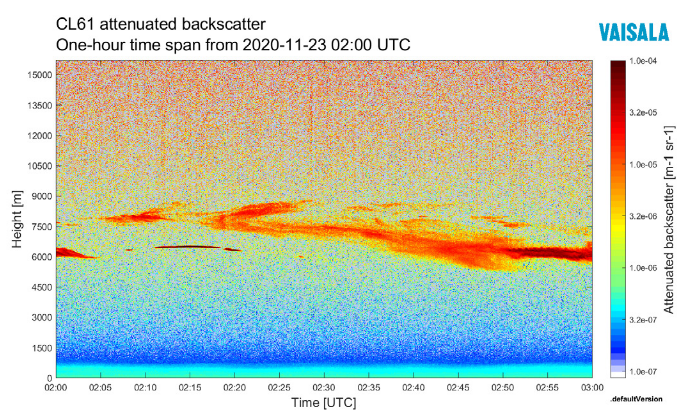
The performance improvements in the evolving Vaisala ceilometer product family are demonstrated in these figures, which compare an ice cloud detected by CL31, CL51, and CL61 at Vaisala testfield, Vantaa, Finland on November 23, 2020. All plots represent the same time period where the ice cloud is seen at above 6 km height.

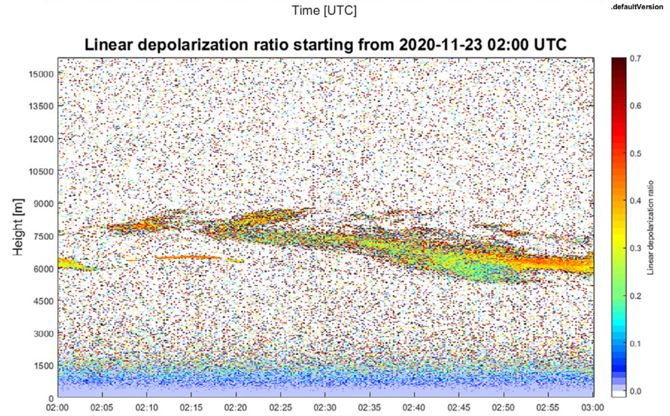
CL31 measurement range is only up to 7.6 km, and therefore the upper parts of the ice cloud are unavailable. CL51 extends the measurement range up to 15 km and CL61 up to 15.4 km, both detecting the full vertical range of the ice cloud. CL61 with depolarization not only measures attenuated backscatter, but also linear depolarization ratio, revealing more information of the cloud properties.

The signal-to-noise ratio (SNR) has also evolved over time. CL61 has 5 times better SNR compared with previous model CL51, and 25 times better compared with earlier model CL31. The improved CL61 performance is best seen in the amount of details detected. Apparent signal level differences are the result of calibration differences whereof the CL61 uses built-in cloud calibration factor for attenuated backscatter profile (according to O'Connor et. al. (2004) method).



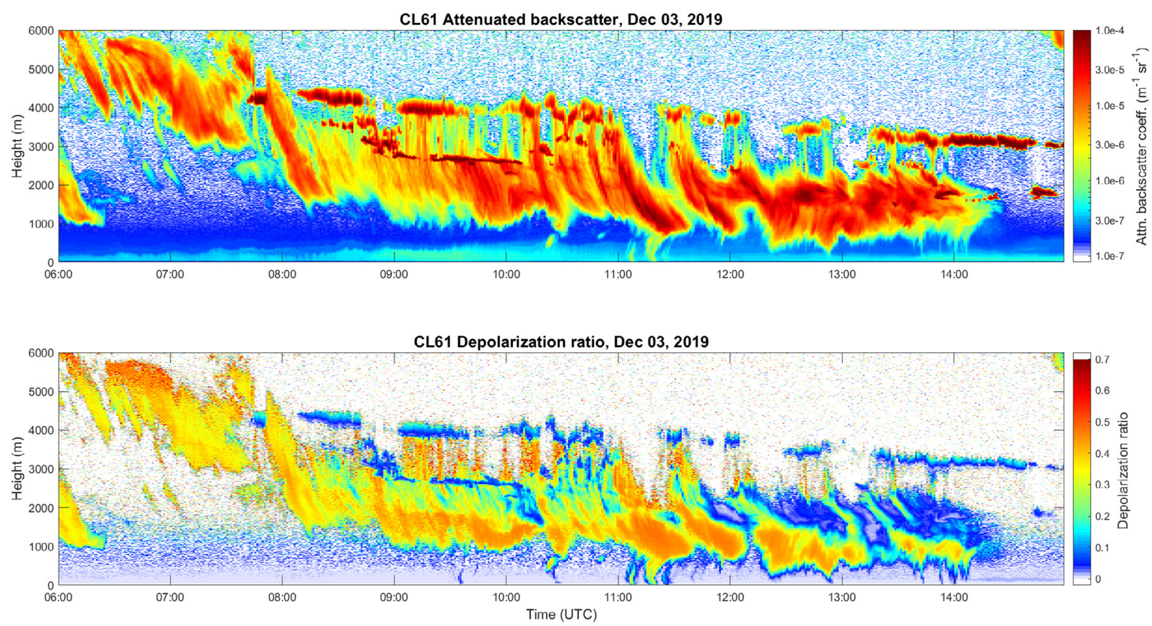



# 5 Ice / liquid clouds

Cloud height information is crucial for aviation, however, the increased understanding of cloud types give more information to evaluate the potential risks: for example understanding of presence of supercool liquid cloud and its height give more information than just reported cloud base height of a cloud. Cloud type information is also usable for several meteorological studies, for example when investigating the effects of clouds to solar energy or radiation balance and much more. Different types of clouds, namely ice clouds versus mixed phase or liquid clouds, show different characteristics in both: attenuated backscatter and linear depolarization ratio.

The following example measured in Finnish Lapland on December 3, 2019 show both ice clouds and liquid layers in between and above the ice clouds and these can be easily differentiated from each other at different times and height levels.




Ice clouds are seen as relatively strong signal in attenuated backscatter data and as larger depolarization ratio values compared to liquid clouds.
In the image, the ice is present almost all of the time where the attenuated backscatter signal has magnitudes colored with yellow and red and linear depolarization signal colored with yellow and orange.

Liquid clouds, in contrast, show strong attenuated backscatter signal, shown as dark red, and the signal from liquid cloud is typically seen as a shallow layer in attenuated backscatter and linear depolarization data due to the fact that the lidar signal is strongly attenuating in the cloud. Linear depolarization values in liquid cloud are close to zero and multiple scattering effects are usually seen when the light is scattered multiple times form the spherical cloud droplets, specifically when the light is transmitting deeper in the cloud (higher depolarization values towards the top of the layer).

**Differentiation of ice and liquid clouds**

**Ice clouds**

- Relatively strong attenuated backscatter signal
- Fewer ice crystals result in seeing through or deeper inside the cloud
- Higher linear depolarization ratio due to irregular shapes of ice crystals

**Liquid clouds**

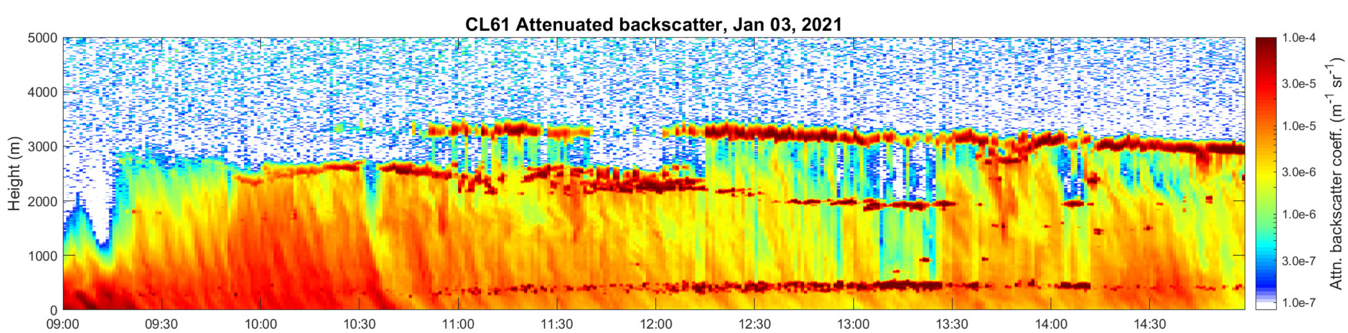
- Strong peak in attenuated backscatter
- Signal attenuating rapidly inside the cloud due to large number of small cloud droplets
- Low linear depolarization ratio due to spherical nature of liquid droplets

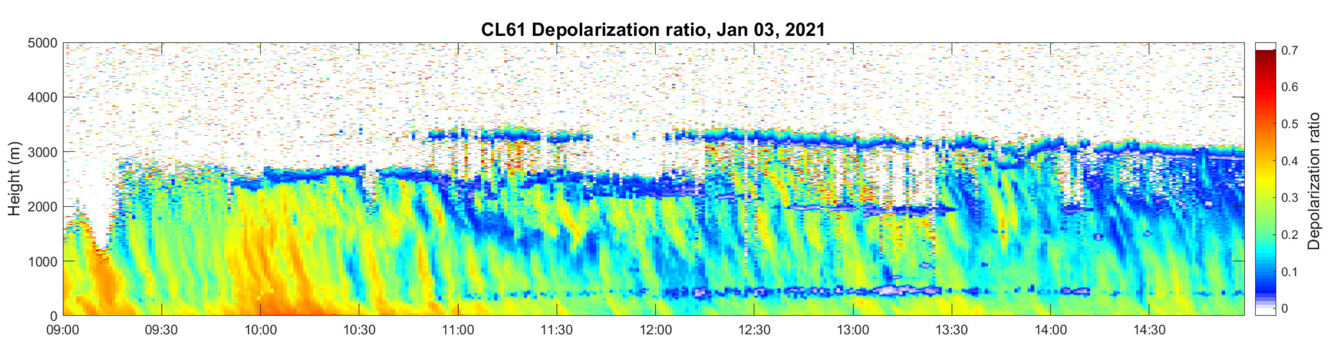
# 6 Precipitation type

Falling precipitation can be seen with ceilometer and precipitation type is distinguishable now with CL61 specially using the depolarization ratio information. In snowfall, the linear depolarization ratio values are larger (>0.2) and distinguishable from raindrops and drizzle which shows smaller values.

The example of snowfall reaching the ground, measured in Finland January 3, 2021, is visible as follows (note liquid layers present in between and top):

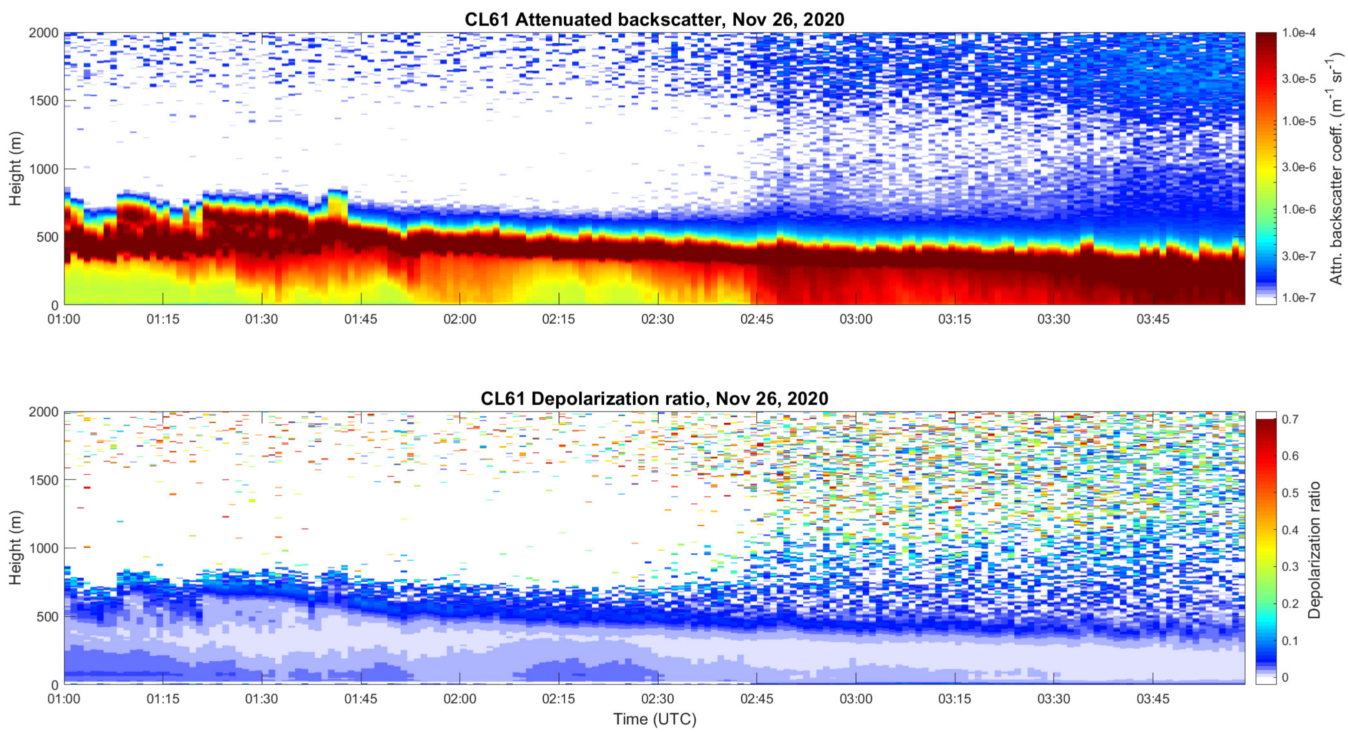
In some cases, the lidar signal is attenuating in snowfall, as seen between 09:00 and 10:00 UTC, i.e. no liquid cloud base is visible. However, in many cases the liquid cloud base is visible above the snowfall, as seen after 10:00 UTC. In this example, there are multiple liquid cloud layers visible in the data, as can be distinguished by strong attenuated backscatter signal and low depolarization ratio values in those layers.

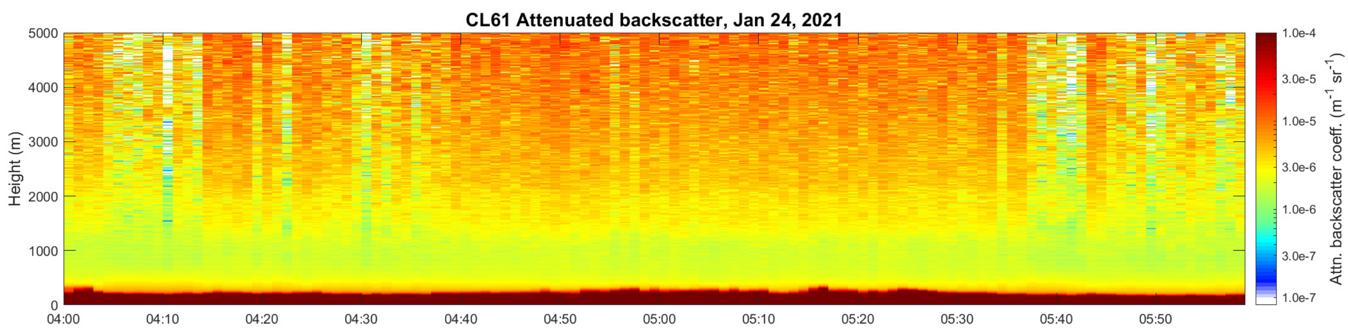
Liquid precipitation is distinguishable from snowfall based on the linear depolarization measurement where the precipitation signal is close to zero.

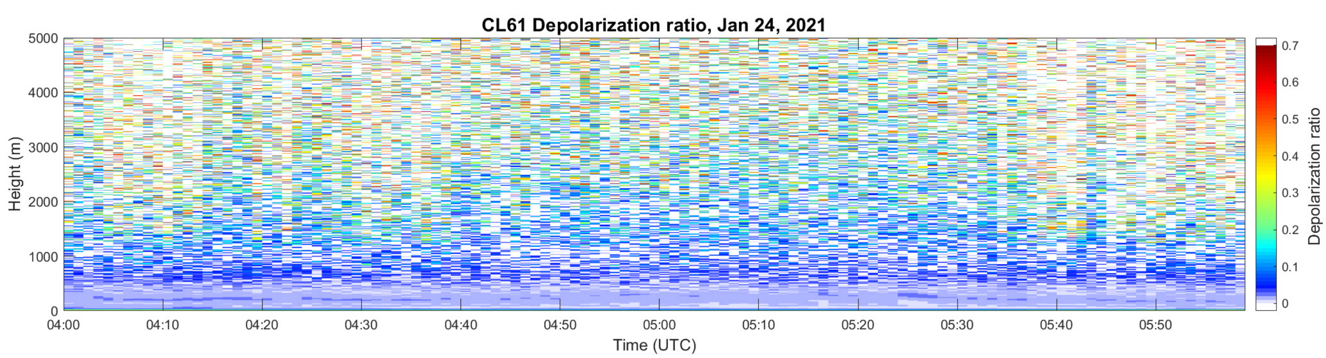
In the following example, measured in Finland in November 26, 2020, the raindrops are falling from the cloud above. Falling precipitation is not always reaching the ground, as can be seen for example between 01:15 and 01:30 UTC. After 2:45 UTC, the rain is continuously reaching the ground.



# 7 Fog monitoring

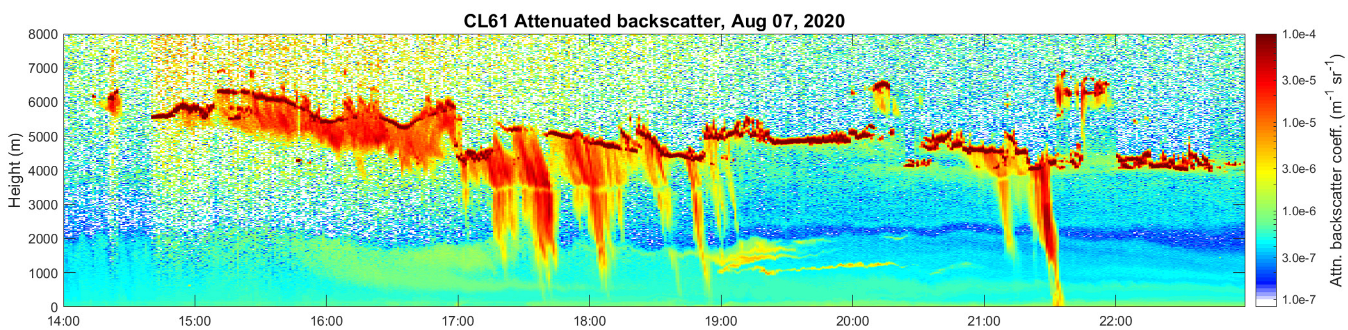
Observing fog and its formation is especially an interest at the airports due to aviation safety but also for people's every-day life as it can have an effect on road safety or simply air temperature. Fog can be effectively monitored with a ceilometer. The response from a fog is visible as a strong peak in attenuated backscatter at ground and low linear depolarization ratio values. The signal is usually attenuating in the fog so that no signal above the fog layer is visible (particularly in thick fog cases). Fog case is shown in the data example measured in Finland on January 24, 2021, during the whole time period from 04:00 and 07:00 UTC. Stronger background noise above the fog layer (yellow and orange colors) is caused by the measurement set to operate with low gain preventing the measurement signal to be saturated due to a strong response signal from the fog.

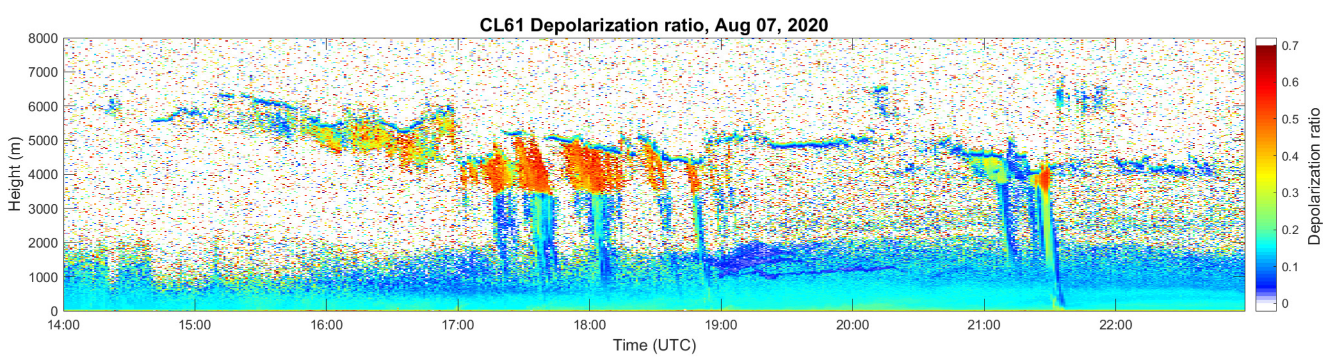


# 8 Melting layer

Melting layer is (if present) visible with ceilometer when looking at the data inside the precipitation region. In ceilometer attenuated backscatter data, the melting layer can be distinguished as so called “dark band” (in contrast to bright band in radar data). Melting layer is visible in the example measured at Cardington, UK on August 7, 2020 between 17:15 and 18:15 UTC above 3000 m. In this case, the melting layer can be verified from linear depolarization ratio, as the linear depolarization ratio values are higher (between 0.4 and 0.5) corresponding falling ice crystals, and lower below the melting layer (below 0.2) corresponding raindrops. In this specific case the precipitation is not reaching the ground at all times. Melting layer detection is useful when estimating the potential hazardous icing situation, as well as for other meteorological studies.



# 8 Icing conditions and supercooled liquid clouds

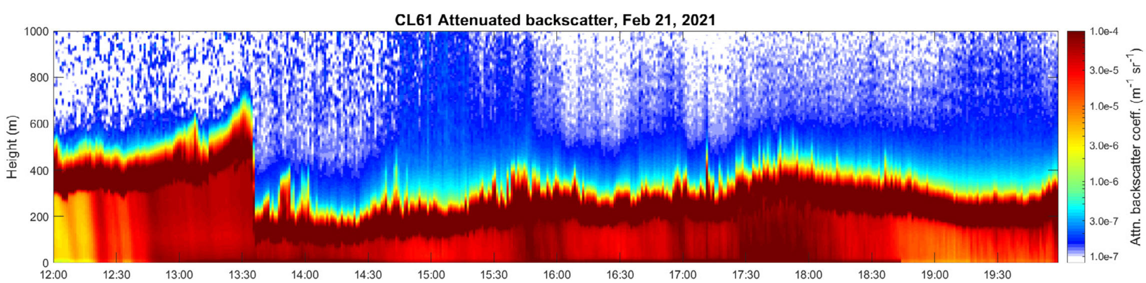
Icing conditions are possibly identified from ceilometer data especially by utilizing information of time and altitude at which a supercooled liquid cloud is present. Supercooled liquid cloud droplets are cloud droplets in liquid form in temperatures below zero. In case such droplets collide with a surface (i.e. wind turbine blade, airplane etc.) the droplet freezes on the surface. As ceilometers are not measuring the temperature profile in the atmosphere, the air temperature can be estimated by using the meteorological knowledge or with additional measurements. Air temperature is usually decreasing with height in troposphere and, therefore, the air temperature can be roughly guessed based on the knowledge of surface temperature. In case of distinguishable melting layer, it is easier to give rough estimate where the temperature has decreased below zero in the atmosphere. Liquid clouds that are above the melting layer most certainly contain supercooled liquid droplets which in turn can be hazardous for example for aviation. In case the ground temperature is below zero, the liquid cloud layers above probably contain supercool droplets, potentially causing icing already at lower altitudes for example for wind turbines. Icing may also occur in case of freezing rain or freezing fog.

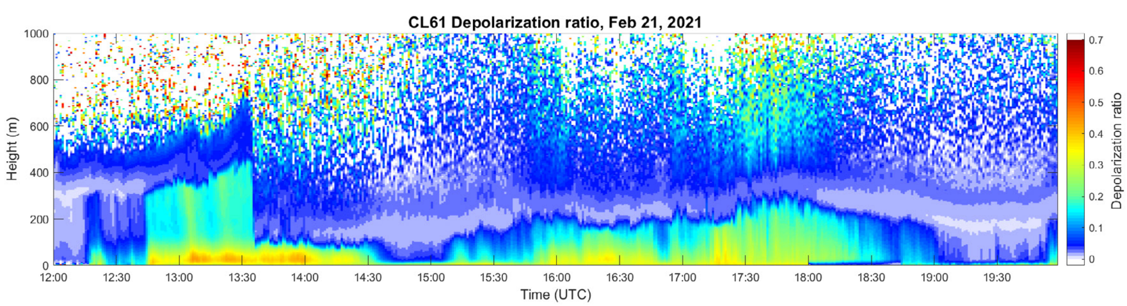
*Illustrative example only*

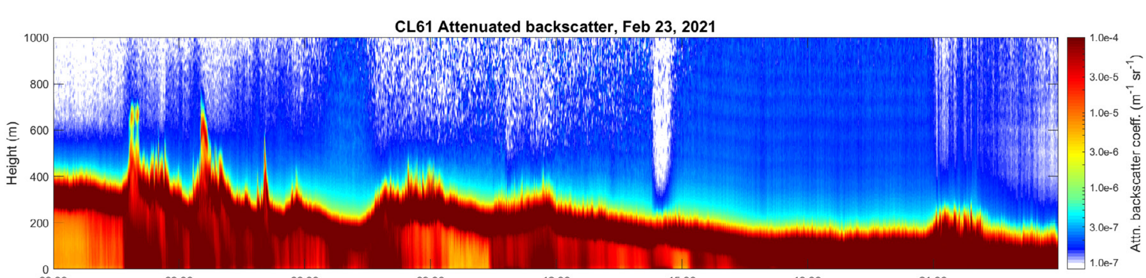
# 9 Freezing rain

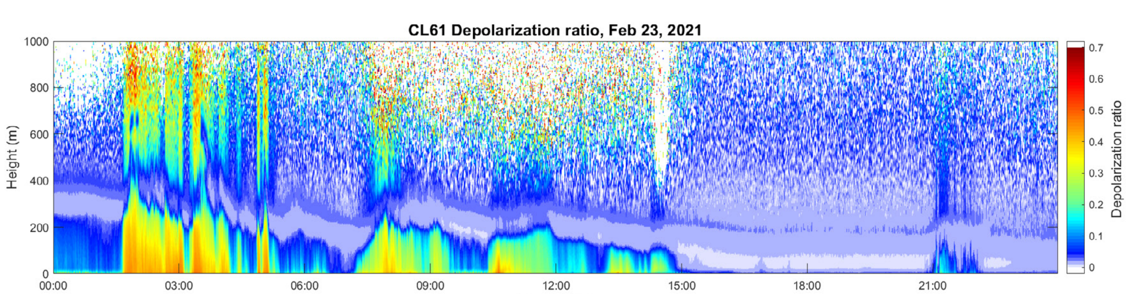
Freezing rain event occurs when there are supercool raindrops falling during air temperatures below zero, leading to potentially severe ice formation on structures. Freezing rain can be extremely hazardous for several every-day functions that touches everyone's lives: for example road safety, aviation, and power grids.

Freezing rain events were measured at Vaisala test field in February 21 and 23, 2021. Clearest signal of freezing rain events can be seen in February 21, between 14:30 – 15:15 UTC and 19:00 – 20:00 UTC and in February 23rd after 15:00 UTC when there is precipitation reaching the ground, linear depolarization ratio suggesting spherical raindrops and at the same time air temperatures were measured below zero with additional temperature measurements. During these time periods, multiple human observations reported freezing rain as well as additional Vaisala instrumentation, including present weather sensors like Vaisala Forward Scatter FD70.



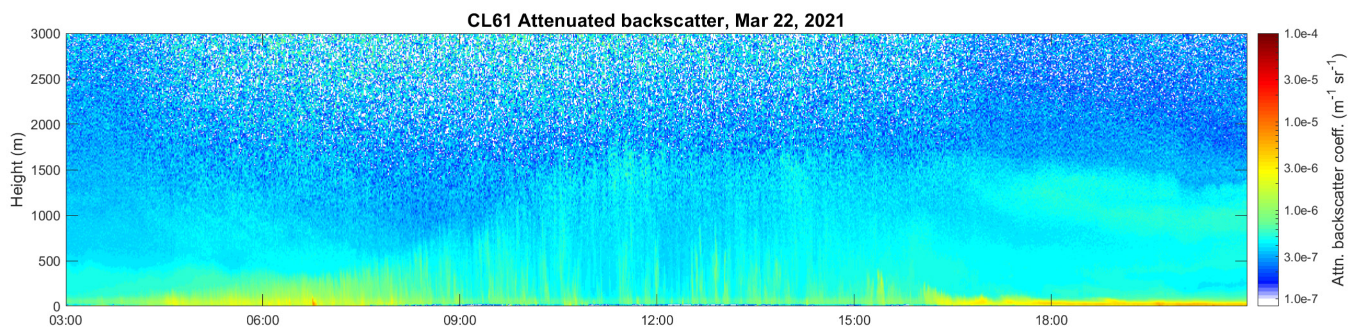



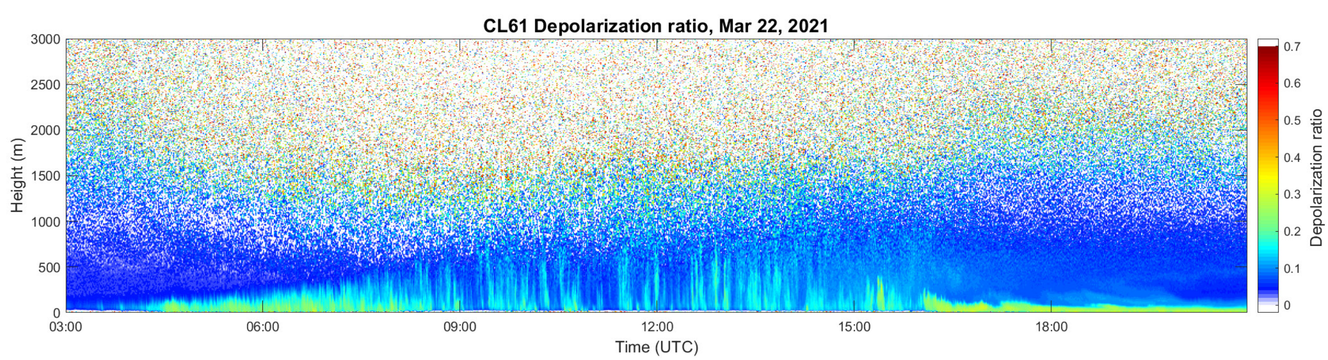



# 10 Boundary layer analysis

CL61 Ceilometer attenuated backscatter and linear depolarization ratio data can be used for boundary-layer analysis. Boundary layer analysis is important for example for air quality, numerical modeling and meteorological studies. In the example below, measured in Finland on March 22, 2021, the evolution of boundary layer during a clear day is well detected with a ceilometer. The growth of the daytime boundary layer is clearly visible from the aerosol signal and at night time residual layer is visible especially after 17:00 UTC. Shallower boundary layer in the early morning is also visible.

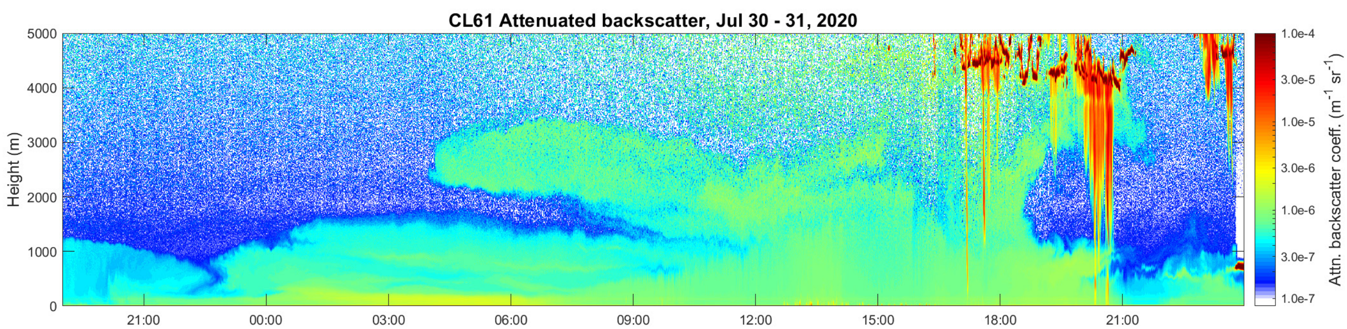


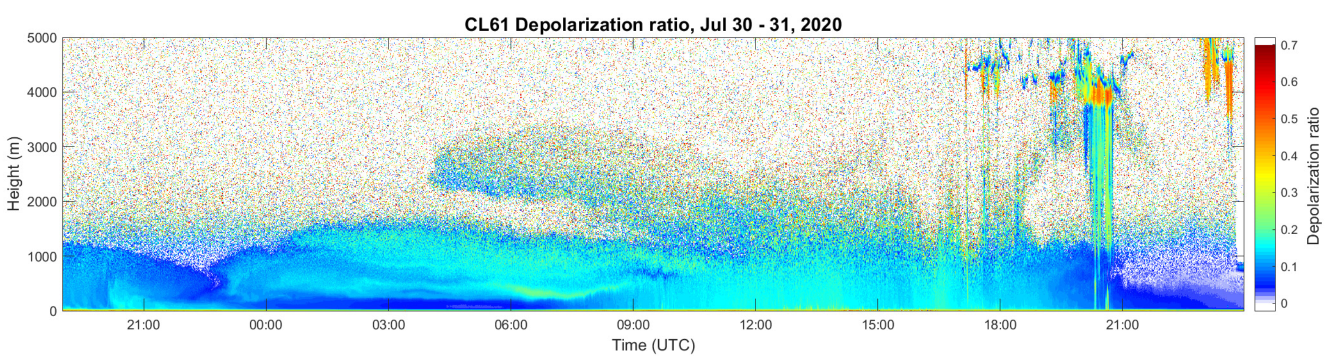



The other example, measured in Cardington, UK on July 30 to 31, 2020, represent different aerosol layers mixing in the boundary layer. The data measured with CL61 with depolarization reveal different aerosol layers and different properties of the layers can be observed.

For example in the case below, the aerosol signal below 2000 m and another layer between 2000 and 4000 m show different characteristics when looking at the linear depolarization data, suggesting different type and source of the aerosols.

The mixing of the upper layer to the lower layer is visible after 12:00 UTC. Differences in linear depolarization ratio in each aerosol layers may help classifying the aerosol types and sources, and furthermore, used as complementary measurement with other instrumentation.



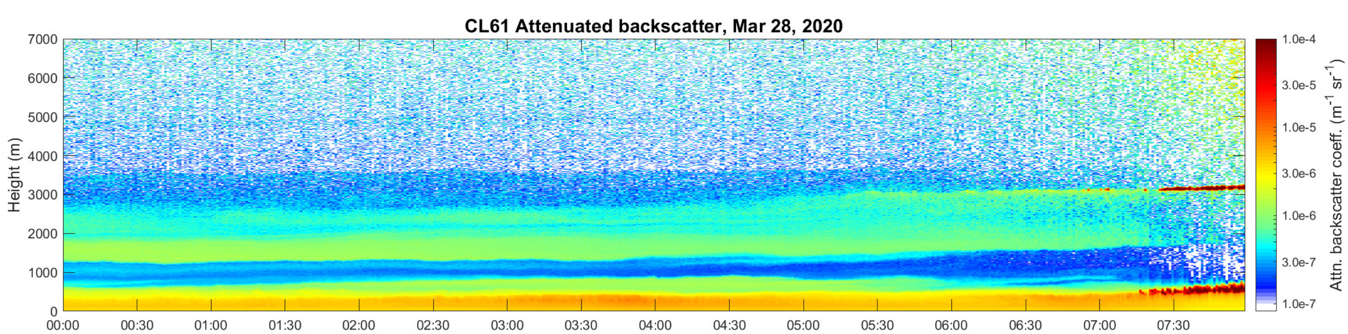



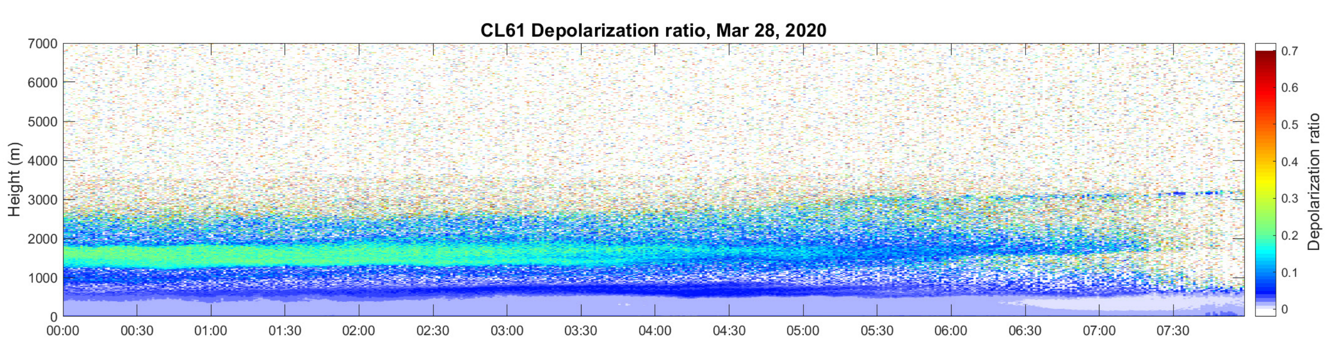
# 11 Dust and sand layers

Different kind of elevated aerosol layers are important for example for air quality and aviation. Several meteorological studies have been conducted to increase the understanding of characterizing different aerosol types by combining different kind of measurement systems, including remote sensing instruments, and modeling.

The following example was measured in Cardington, UK on March 28, 2020, Above the boundary layer signal, there is an elevated aerosol layer showing different characteristics.

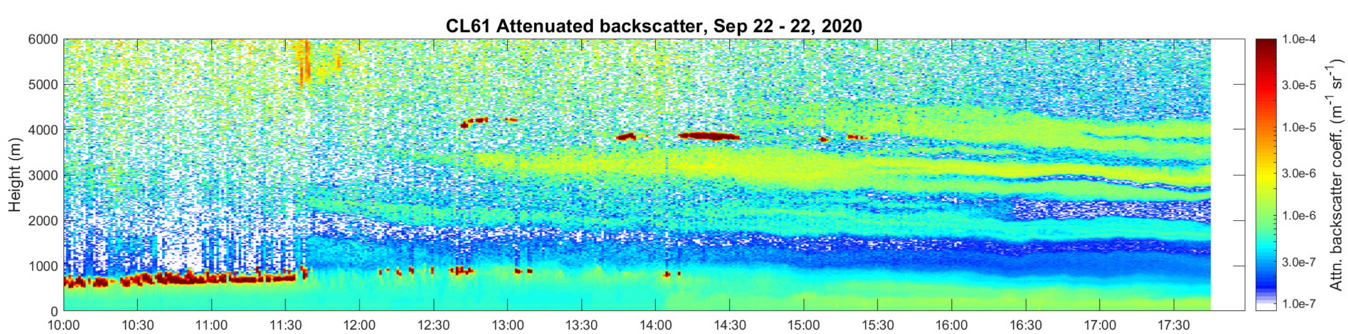
Additional case analysis by the UK MetOffice suggested that the boundary layer aerosols are pollution or smoke and elevated layer above is a mixture containing mineral dust (full test report by UK MetOffice available by request from Vaisala – © British Crown copyright 2020, Met Office). Additional analysis was done by combining information from Raymetrics research lidar and HYSPLIT trajectory analysis.

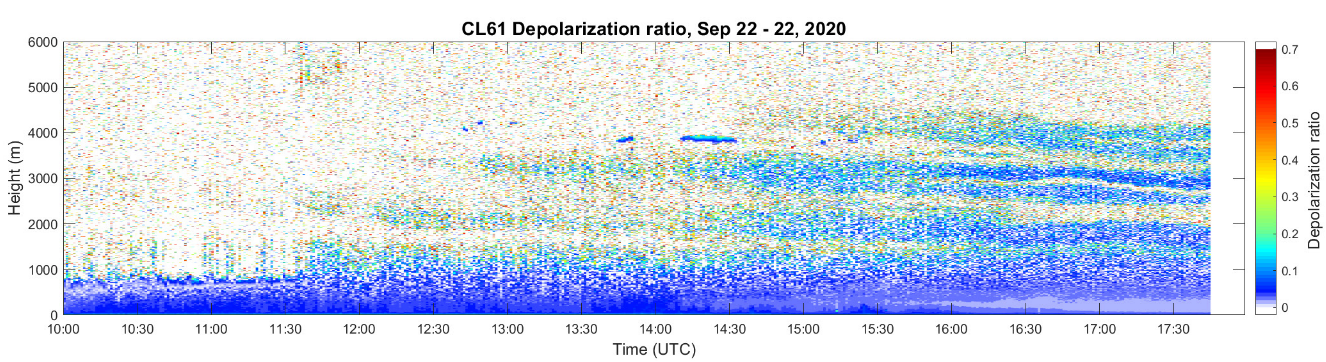



# 12 Smoke from wild fires

On September 22, 2020, the smoke plumes from Californian wild fires were measured in Finland. Smoke layers were detected between 1000 and 4000 meters after 11:30 UTC and can be distinguished both at attenuated backscatter and depolarization ratio images. These depolarization values of 0.06 to 0.08 correspond well with known literature.

# 13 Volcanic ash

Detection of volcanic ash is a crucial new capability of the CL61. The improved SNR helps detect high elevated aerosol layers that can cause a severe safety risk for aviation. CL61 linear depolarization ratio provides additional information for identifying volcanic ash and serves as a valuable validation data source for warning systems.

On the island of La Palma in the Canary Islands, the Cubre Vieja volcano erupted for three months (from September 19th to December 25th, 2021). Lava flows damaged property, ash plumes led to disruptions to air travel and poor air quality caused by volcanic ash and noxious gases impacted health of local inhabitants.

The CL61 was installed at courtyard of El Paso town hall, located to the north of Cumbre Vieja at 723 meters above sea level. to measure volcanic ash layers aloft. The La Palma International airport is located near the east coast town of Santa Cruz.

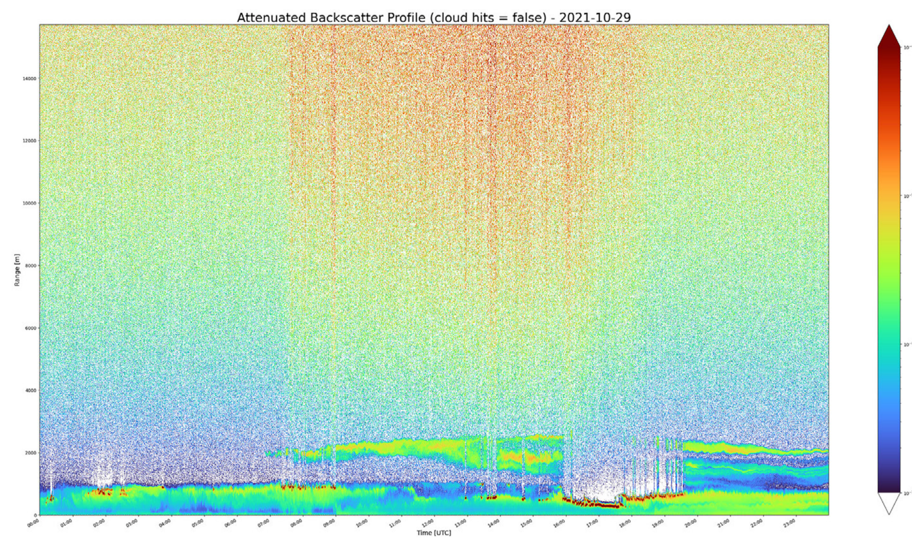
*On the left, CL61 Lidar Ceilometer installed at El Paso Town Hall (picture by AEMET). On the right, map of La Palma with marker indicating the CL61 location north from Cumbre Vieja (picture Google Maps).*

The following study of using CL61 with depolarization capability to observe volcanic ash at La Palma was made in co-operation with AEMET.

The CL61 data is used for understanding the volcanic ash layer movements above La Palma but also to warn the people of El Paso of possible ash rain. Most of the time the prevailing winds have driven the ash plumes towards southwest but occasionally the plumes have also been detected above El Paso and the airport. Precautionary measures were then issued to the public, such as guidance to stay indoors or to wear masks and protective clothing, and delays to air travel due to high ash concentrations.

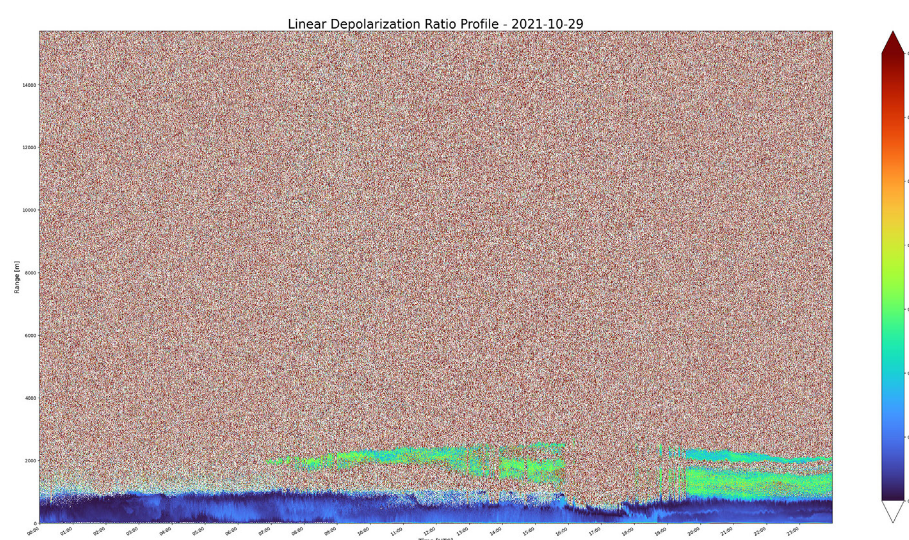
## Volcanic ash above the boundary layer

Here are a few measurement examples from CL61 volcanic ash measurements. The first example shows the attenuated backscatter profiles in a time/height plot. In this picture we see a strong intensity signal within boundary layer (up to 1,000 meters) but also a layer aloft at about 2,000 meters from 07:00 UTC onwards. There are also clouds forming due to ash particles close to the top of the boundary layer which appear as dark red signals on the plot.




*CL61 Attenuated backscatter profile for October 29 2021*

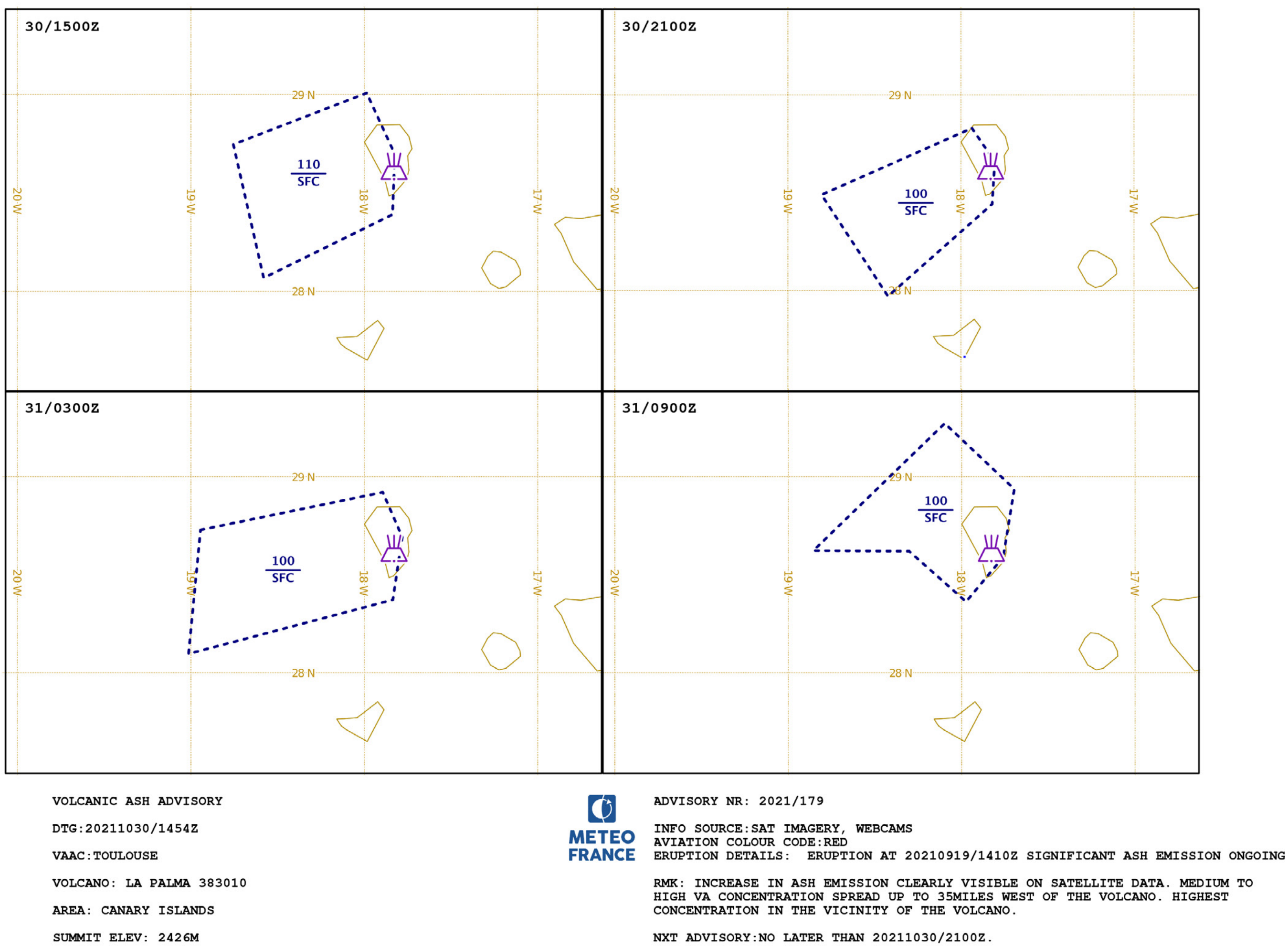
When we observe the same day with the depolarization signal, which is based on depolarization ratio between parallel and cross polarized signals, we can clearly see the volcanic ash layer aloft above the boundary layer. The ash layer is seen with a depol ratio of 0.3 to 0.4, and in this case the layer aloft travelled above the La Palma island and did not cause ash deposition on the ground level. The cloud layer at the top of boundary layer from 16:00 UTC to 20:00 UTC is a liquid cloud layer as it has depol ratio close to 0.0, as are also all the other clouds formed at the top of the boundary layer on this day.




*CL61 depolarization ratio profile on October 29 2021*

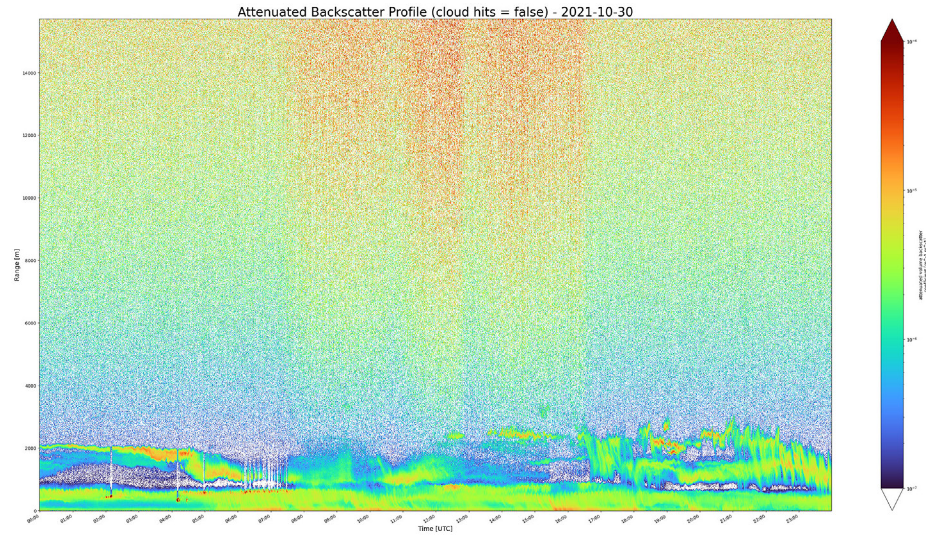
## Volcanic ash rain

This example shows volcanic ash rain which was also observed on the ground level. The first picture is showing the Volcanic Ash Advisory Center (VAAC, Meteo France Toulouse) forecast of ash layer on October 30, 2021. From this we can see the forecast indicating the layer is above the town of El Paso.



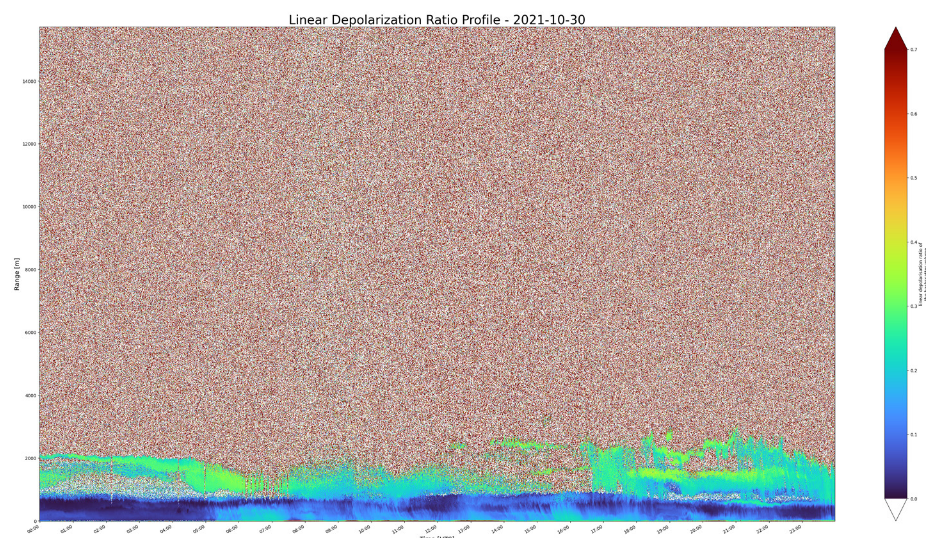

*VAAC forecast for October 30, 2021 at La Palma (picture by VAAC)*

The CL61 attenuated backscatter profile on October 30, 2021 shows high signal on boundary layer as well as layers above it. There is an especially high signal close to ground from 05:00 UTC to 22:00 UTC.




*CL61 attenuated backscatter profile on October 30, 2021*

When investigating the depolarization ratio profile for the same day, we can see the volcanic ash layer aloft but also much of the volcanic ash within the boundary layer. We can see the ash layer aloft above the boundary layer at around 2,000 meters height all day. An interesting observation in this plot is the volcanic ash rain which caused an accumulation of ash on the ground. The depolarization signal indicates the deposition which observers also saw on the ground. Again, the depol ratio values at 0.3 to 0.4 are well in line with the anticipated volcanic ash depolarization ratio signal.




*CL61 depolarization profile on October 30, 2021*

**Summary**

The Vaisala Lidar Ceilometer CL61 with depolarization capability shows great benefits in different applications. CL61 can be used not only for cloud base height measurements, but also for characterizing different particles: liquid droplets, drizzle and raindrops, snow and ice crystals, dust, volcanic ash and sand. CL61 is more effective than traditional ceilometers for detecting icing and freezing conditions and for mixing layer height detection. CL61 has compared favorably with different research-grade lidars in measurement campaigns in different climates.

VAISALA

vaisala.com/CL61

Scan the code for more information

Ref. B212377EN-B 