European networks observing the atmospheric boundary layer: Overview, access and impacts

Chapter 2a: Automatic low-power Lidar and Ceilometer (ALC):

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Authors	Frank Wagner, Alexander Geiß, Francesca Barnaba, Livio Belegante, Annachiara Bellini, Joelle Buxmann, Henri Diémoz, Daniel Fenner, Simone Kotthaus, Martin Osborne, Rolf Ruefenacht, Jaume Ruiz de Morales Céspedes, Melania Van Hove Prepared with input from various manufacturers: ● Stéphane Victori, Cimel ● George Georgoussis, Raymetrics S.A. ● Justin Fisher, Droplet Measurement Technologies ● Reijo Roininen and Minttu Tuononen, Vaisala ● Bernd Fröhlich, Klaus Riegler and Keith Wilson, Lufft - Ott Hydromet

COST Association AISBL | Avenue Louise 149 | 1050 Brussels, Belgium
T +32 (0)2 533 3800 | F +32 (0)2 533 3890 | office@cost.eu | www.cost.eu

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Introduction

Lidar and modern ceilometer instruments are using the same measurement principle. For many years, the development of high-power lidars and low-power ceilometers were evolving in parallel with different aims. The high-power lidars had the aim to receive as much as possible accurate and independent information from the atmosphere; these were historically networked in the EU within EARLINET (now part of ACTRIS) and operated with a specific weekly schedule. The low-power automatic ceilometers focused on automated, eye-safe and continuous monitoring of the troposphere and on the detection of clouds. These devices are also named as automatic lidar ceilometers or automatic lidar-ceilometers highlighting the use of the lidar measurement principle.

Progressing within the COST-action ToProf (Towards operational ground based profiling with ceilometers, doppler lidars and microwave radiometers for improving weather forecasts - ES1303, 2013-2017), and more recently within PROBE, ceilometers improved accuracy and associated data quality has been demonstrated to be suitable for aerosol particle retrievals, as the attenuated backscatter coefficient. The Eumetnet activity E-PROFILE as part of the EUMETNET Composite Observing System (EUCOS) has supported improvements in ALCs over time and is now benefiting from this achievement. Also, the high-power lidars are getting more and more automated. Furthermore, automatic low-power lidars were developed which need more power than ceilometers but less than high-power lidars. For distinguishing the different information content and accuracy as well as to address the degree of automation, the terms “Aerosol high-power aerosol lidars (AHL)” and “Automatic low-power lidars and ceilometers (ALC)” are now used by the ACTRIS topical centers CARS (Centre for Aerosol Remote Sensing) and CCRES (Centre for Cloud Remote Sensing). The acronym ALC will therefore be used in this report as consistent naming for ‘Automatic Low-power lidars and Ceilometers’, ‘Automated Lidar Ceilometers’ and, ‘Automated Lidar-Ceilometers’).

This report provides an overview of operating ALCs, including introduction to sensor, products, manufacturers, instrument types, instrument setup and required regular maintenance on site, calibration, measurement configuration, data formats, QA/QC methods and retrieval methods.

The structure of the document follows the deliverable requirements of PROBE. Part 1 gives a general overview of Automatic low-power Lidars and Ceilometers, their products and available instrument types. Part 2 describes instrument operation, which includes installation, calibration, maintenance and QA/QC procedures. Part 3 refers to data harmonization and standardization. In Part 4, available processing and retrieval algorithms are presented. For more detailed information on the individual parts, the reader is referred to the appendix.

Applicable PROBE documents and reports

Virtual Mobility Grants (VMG)

- [VMG 01] Osborne, Martin (2022): Implementation of temperature dependent corrections to the overlap functions of CHM15k ALC in the E-PROFILE processing chain, OSBORN-VM-W2-ABL
- [VMG 02] Bellini, Annachiara (2022): Overview of the current methodologies for the retrieval of aerosol extinction and mass concentration profiles from Automated Lidar-Ceilometers, BELLIN-VM-W2-AER
- [VMG 03] Buxmann, Joelle (2023): Investigating the seasonal fluctuations of the CHM15K Ceilometer calibration constant, BUXMAN-VM-W3-ALC

- [VMG 04] van Hove, Melania (2023): Seasonal variation in the Rayleigh calibration factor of Automatic Lidar-Ceilometers: amplitude across Europe and possible explanations, HOVE-VM-W2-ALC, https://zenodo.org/doi/10.5281/zenodo.10950426
- [VMG 05] Osborne, Martin (2023): Project to compare ALC retrieval algorithms on common data sets, OSBORN-VM-W2-ALC

Short Term Scientific Missions (STSM)

- [STSM 01] Ruiz de Morales Céspedes, Jaume (2023): Liquid cloud calibration algorithm for ALC, CESPED-ST-W4-ALC

Standard Operating Procedures (SOP)

Available for (not online so far)

- Vaisala CL31
- Vaisala CL51
- Vaisala CL61
- Lufft CHM15k

Part 1 General overview

Introduction

ALCs are low-power, low-maintenance, low-cost elastic backscatter lidars, usually operating at a single wavelength in the near-infrared spectral region (but some dual-wavelength ALC are available). A transmitter emits eye-safe laser pulses with low power and high repetition frequency into the atmosphere, the back-scattered light is captured by a receiver. From the round-trip time, a profile of the range-corrected signal can be obtained from which the attenuated backscatter can be derived by applying a calibration value. Some ALC measure depolarization as well. In contrast to high-power lidars that are often subject to intermittent schedule operation and research environment settings, ALC can be operated continuously (24/7) with very little maintenance.

Products

Two main products are provided by ALC: The profile of attenuated backscatter which is the range-corrected and overlap-corrected signal divided by the calibration value, and the cloud base height. Recently developed ALC devices also provide co- and cross-polarized attenuated backscatter to derive the linear volume depolarization ratio. The cloud base height is derived from attenuated backscatter observations by the proprietary instrument firmware. Some ALCs provide heights of multiple cloud layers at a time and cloud cover products are also available. One should be aware that the same cloud base altitude differs for different ALC types due to different definitions implemented in the firmware with approx. 50-100m difference for liquid water clouds (Appendix E).

Higher level products that can be obtained from ALC observations include cloud type, detection of precipitation and hygroscopic particle growth (fog formation), visibility information, aerosol layering including height of the atmospheric boundary layer (ABL), or aerosol optical properties (e.g. particle backscatter coefficient). These products usually require additional assumptions and auxiliary information (e.g. atmospheric temperature and pressure profiles).

Table 1 provides an overview on the processor chain and product levels for ALCs that are also used within E-PROFILE. Raw data output by the manufacturer firmware either in ASCII or netCDF format (Part 3) is referred to as level L0 data. Note that products obtained from manufacturer software at Level L0 have different data quality and uncertainty and can vary with firmware version. In addition, note also that file and variable naming conventions differ between ALC models.

To obtain a standardized and harmonized product from all ALCs in netCDF format with the same naming convention (example: CF-1.10), data is processed to Level L1 by using the Raw2L1 tool (Part 4). Within this step the range corrected ALC signal is normalized and missing information is added. A table giving an overview on the available products from several common ALC is shown in the Appendix B. Attenuated backscatter provided by the manufacturers software by applying a factory calibration and sometimes with overlap correction is referred to as uncalibrated attenuated backscatter or normalized range corrected signal. Studies and long-term analyses have shown that calibration constants can vary over time due to instrumental effects or degradation [VMG 03, VMG 04]. Hence, regular calibration and additional corrections are necessary which are applied in the processing to level L2. This harmonized and quality controlled level L2 data can be further used for processing level L3 products which are explained and demonstrated by the working groups for aerosol (WG2-Aerosol), ABL height (WG2-ABL) and fog alert (WG2-Fog).

It is worth mentioning that E-PROFILE provides a service to process ALC data up to Level L2 at the moment with an option to determine ABL height in the near future.

Table 1: ALC product levels established within E-PROFILE and the ALC community.

Level	L0	L1	L2
Description	**Raw data** Data output by manufacturer firmware in ASCII or netCDF format: ● Own naming convention ● Variable file length ● Varying scope of information See Part 3 and Appendix B for details on data formats.	**Standardized and harmonized L0** Standardized and harmonized data/file format with necessary info not provided in raw data (e.g. instrument settings, geolocation information). Following CF-conventions. Same units.	**Corrected and calibrated signal using auxiliary information** Reliably calibrated and corrected data. This harmonized data comparable across all ALC models can be used for further retrievals or synergy products as L3 level: ● Aerosol (optical properties, mass) see WG2-Aerosol ● ABL height see WG2-ABL ● Fog alerts see WG2-Fog
Products	**All:** ● Range corrected signal ● Cloud information ● Visibility information ● Housekeeping data ● Status flags **Optional (model dependent or additional license needed):** ● ABL height ● Linear volume depolarisation ratio	● Normalized range corrected signal ● Manufacturer overlap function	● Attenuated backscatter (overlap corrected, dark background corrected, water vapour absorption corrected and calibration constant applied) ● Quality flags ● Uncertainty
Methods		RAW2L1 tool (see Part 4)	● Rayleigh calibration ● Cloud calibration ● Overlap correction ● Background correction ● Water vapour absorption correction

Manufacturers/instrument types

A range of manufacturers offer various ALC models on the market, which differ in their specifications and can therefore be suitable for aerosol or cloud measurements to varying degrees. A list of available devices is shown in Table 1. Capabilities for quantitative aerosol profiling depends on the signal-to-noise ratio, the stability of the single models, possible application of correction procedures and calibrations.

Table 2: Main specifications of ALC models from different manufacturers.

Manufacturer	Model	Wavelength***	Max range*	Min resolutions	Average Laser Power	Blind zone**	Detection type	Polarization
Ott Hydromet (former Lufft)	CHM15k	1064 nm	15 km	5 m, 2 s	50 mW	~220 m	APD Photon counting	
	CHM8k	905 nm	8-10 km	5 m, 2 s		110 m	16 bit analog	
Vaisala	CL61	910.55 nm	15.4 km	4.8 m, 5 s, 10 s depol	30 mW	35 m	APD analog	yes
	CL51	910 nm	15.4 km	10 m, 6 s	19.5 mW	41 m	APD analog	
	CL31	910 nm	7.6 km	5 m, 2 s	12 mW	10 m	APD analog	
Raymetrics	RAP	1064 nm	>14 km (depol. ~up to 3-4 km)	12 s, 3.5 m	150 mW	250 m	Analog and photon counting	yes
Droplet MT	MiniMPL	532 nm	> 15 km	5 m, 1 s	10 mW	120 m		
Cimel	CE376	532 nm / 808 nm	15 km / 7 km	7.5 m, 0.8 s	35 mW / 15 mW	100 m		Optional
Eliasson	CBME80B	905 nm	7.6	5 m, 15 s				
Campbell Scientific	SkyVUE	912 nm	8-10 km	5 m	48 mW	45 m	APD analog	

* As stated by the manufacturer. Corresponds to the range of the signal, not to the range where products are available. This depends on the signal-to-noise ratio which can vary in presence of aerosol or clouds.
** The Instrument blind zone due to incomplete optical overlap. For simplicity and practical reasons we provide here the height where the overlap is 3%, corresponding to a 97% correction. Has influence on the detection of very shallow ABLs but can still allow for cloud base detection.
*** temperature dependent wavelength changes for some devices due to insufficient thermal stabilization

Additional model-specific information:

- Cimel, Lufft CHM15k and Droplet MT MiniMPL use photon counting technology.
- Raymetrics RAP works with diode pumped solid state Nd: YAG laser.
- CIMEL CE376 works with both laser (Nd:YAG for 532nm) and laser diode (for 808 nm) .
- Vaisala, Campbell and Lufft CHM8k work with InGaAs laser diode and APD analogue detector.

- Raymetrics Aerosol Profiler (RAP) has built-in “dark measurement“ capability, as well as Telecover test and motorized telescope/laser field of view alignment. Automated delta 45 depolarisation calibration is also available.
- Droplet MT MiniMPL has 2 versions reporting up from 50 m or 100 m minimum range, respectively. MiniMPL has the possibility to add a scanner for multiple, programmable view angles. MiniMPL has a “normalized relative backscatter” product which uses key instrument calibrations to remove instrument-to-instrument variations between units.
- ABL heights can be provided by Vaisala, Campbell and Lufft devices by the firmware with an additional software license needed for Vaisla and Campbell instruments
- Lufft devices have an onboard memory to save data which prevents from data loss in case the data transfer is interrupted

Part 2 Instrument operation (D4.1)

Instrument set-up

ALCs need to be installed on a secure, stable and leveled surface (e.g. concrete base). Open view to the sky (e.g. no tree branches) is mandatory. Although ALC operate eye-safe lasers that do not require specific security clearance in most cases, regulations applicable for the specific measurement location should be checked. If more than one ALCs are installed, a minimum distance of approximately 8-10 m or tilting is needed for instruments with the same wavelength to avoid possible optical interference. To avoid specular reflections on ice crystals in cirrus clouds, a slight tilting of the instrument can be necessary and is already implemented for instance in the Vaisala CL61 with an angle of 3-4 degree. If tilting is applied, it is important that tilting angles are recorded or saved in the processing to level L1 in order to apply a tilting correction for cloud products if not yet done by the firmware. However, the manufacturer's manuals must be checked for further specific installation details.
ALCs can be configured via a web interface, a serial connection or SSH. Data transfer is usually realized via a serial interface or an ethernet connection and data is pushed via FTP/SFTP in NetCDF format or is recorded with an acquisition software when using a serial connection. It is important to use an accurate system clock to get correct timestamps. For some systems a time server (NTP) can be defined and used. Other systems rely on the correct time of the operating system where the acquisition software is running. It is recommended that the operating system synchronizes its time by using a NTP-server.
With variable temporal and spatial resolution settings possible it is recommended to check the instruments SOPs for settings well established within the existing measurement networks (e.g. E-PROFILE). This is also necessary for instrument specific settings having an influence on the measurement performance.

Maintenance

ALCs are low maintenance instruments but this can be highly dependent on the measurement location (e.g. high pollution, snow fall, high humidity) which has an influence on the maintenance frequency.
A regular cleaning of the window is needed and can be checked by visual inspection or at least by monitoring the window condition parameter available for most ALCs in the housekeeping data.

Common situations where window cleaning is likely are strong desert dust events, especially when there is drizzle in addition resulting in wet deposition. But also during the pollen season a higher cleaning frequency can be necessary.
During heavy snowfall it might be necessary to remove snow from the housing when the heating is not sufficient to remove it. This can also be the case for fan intakes which have always to be clear.
For some instruments it is also important to regularly check the desiccant in the instrument housing and replace it if needed to avoid high humidity. Some instruments already provide a relative humidity parameter in the housekeeping data.
The monitoring of other housekeeping data and status flags such as temperatures or laser status can provide information about the device status and any necessary maintenance or replacements.
By following QA/QC procedures, i.e. regular calibrations or dark signal measurements, additional information about possible instrument degradations can be obtained.

Calibration

The reported range-corrected signal after application of the optical overlap correction can be considered to represent the uncalibrated attenuated backscatter, although some devices are calibrated by the manufacturer with unknown accuracy. To derive the absolute value of attenuated backscatter (e.g. required for aerosol studies), two methods for calibration during post-processing are available: the “cloud calibration method” (O’Connor et al., 2004; Hopkin et al., 2019) and the “Rayleigh calibration method” (e.g. Wiegner and Geiß, 2012). Both are utilizing the probed atmosphere and some assumptions to determine a calibration coefficient.

Rayleigh Calibration Method

The Rayleigh calibration method can be applied to ceilometers which measure accurately in the far field. This implies that instrumental artifacts are absent or at least negligible. These are normally devices with photon counting as detection mode and, as an exception, the CL61 device. The method requires an aerosol free layer where the received signal is determined by molecular backscattering. In practice, one needs 3-4 hours of clear sky in a stable atmosphere during night-time. This assures that averages over time achieve a sufficiently high signal-to-noise ratio and consequently one can determine a calibration value. More details are provided in the Appendix A.

Cloud Calibration Method

The cloud calibration method can be applied to ceilometers which measure accurately the backscattered signal from low clouds, namely liquid water clouds. These are usually devices with an analogue detection mode. Normally, a ceilometer based on photon counting suffers from saturation while measuring the signal from low clouds. The method requires that the clouds are formed from liquid droplets. Mixed phase clouds or ice clouds are not suited. The method further requires that the cloud is sufficiently thick and hence the laser beam is fully attenuated within the cloud. This requirement is normally fulfilled for low clouds which are thicker than 300m. More details are provided in the Appendix A.

Calibration of the polarization channels for Ceilometers

Particle depolarisation ratios retrieved from ceilometer measurements are used for aerosol layer identification and the distinction of water and ice clouds. The particle depolarization ratio is one of the primary parameters that can differentiate major aerosol components but only if the measurements are accurate enough. The accuracy related to the retrieval of particle depolarization ratios is the driving factor for assessing and improving the uncertainties of the depolarization products, particularly in the case of ceilometers with polarization channels, which also require depolarization calibration like in the case of lidar instruments. In essence, when emitted, linearly polarized light is predominantly backscattered with the same linear polarization, but it becomes partly depolarized upon interaction with atmospheric targets, which are non-spherical and randomly oriented (Mishchenko and Hovenier, 1995). Typically, the collected backscattered signal is detected using polarization-sensitive techniques by separating the signal into two optical paths: the first (parallel or co-polar) containing backscattered light with the original polarization and half of the depolarized light, and the second (cross or cross-polar) containing the remaining depolarized light (Gimmestad, 2008). Alternatively, some systems rely on detecting the total and cross backscattered signals instead (Engelmann et al., 2016). More details are provided in the Appendix A.

Measurement configuration

Best measurement settings for the Vaisala CL31, CL51, CL61 and the Lufft CHM15k can be found in the corresponding SOPs and are recommended by ACTRIS and E-PROFILE. For instruments where no SOP is available yet a few recommendations are summarized in the following. The temporal and spatial resolution should ideally be similar to that of the devices with available SOPs. With several available setting options for the extent of the measurement data, the most detailed variant should be selected as a guideline for further post-processing with QA/QC procedures.

Raymetrics

For participation in EARLINET as part of ACTRIS the following quality assurance tests are recommended:

- Automated Quality Assurance tests:
  - Automated dark signal measurements
  - Telecover test
  - Automated delta 45 depolarization calibration
- ACTRIS QA:
  - Zero-bin tests report
- Other:
  - Motorized alignment

Droplet MT

- SigmaMPL2015R2.3 or higher version of software is required.
- NETCDF data should be enabled and configured to send to a predetermined network location. Set “netCDFFTP=1” in the INI file. Enter in server details in SigmaMPL through the Configure->Real Time Setup->FTPNetwork->Add/Edit Server.
- Set the automatic reboot option (see manual for details) to avoid loss of measurements in case a timeout of the data acquisition card forces a reboot of the computer.
- Aeronet data should be configured to allow for AOD data to be ingested with the LiDAR data. This can be configured using the Configure->Algorithm Setup->Lidar Equation menu in SigmaMPL. The user has 2 ways to retrieve the Aeronet Data. 1) AOD Enclosure – Select this option and type in the Aeronet Site name as it is listed on the Aeronet website to download the data directly from the Aeronet website. 2) Proxy Server – Select this option and enter in the server details to get the data directly from a proxy server. Once the desired ingestion

method is chosen, the user can choose between downloading Level 1 or Level 1.5 data and looking at AOD, SDA or both data products.

Cimel

The CIMEL CE376 GPN does not require specific conditions when used in its thermal enclosure. For use without a thermal enclosure, the temperature should lie between 23°C +/- 5°C to ensure the stability of the overlap function. Operating it in a room with a window, special attention should be considered with the type and the size of the window to avoid any lens effect and depolarization.

QA/QC

The QA/QC of ALCs can be realized in two complementary ways. On the one hand, as mentioned above, it is important to monitor the housekeeping data on the status of the device in order to detect possible malfunctions or signs of aging which might affect the measurements. On the other hand, the actual measurement data can be used to apply calibrations, correction procedures for e.g. incomplete overlap or instrument-related background as a procedure for evaluating product quality and for improving product quality.

Some Important ALC housekeeping parameters (not available for all ALCs) are:

- Window transmission
- Laser energy/pulses
- Several temperatures (e.g. laser, detector, internal)
- Relative humidity

QA/QC on measurement data:

- Overlap temperature dependence (Lufft) (Hervo et al. 2016), recent work by Martin Osborne [VMG 01]
- Instrument-related background (Kotthaus et al. 2016), recent analysis by Alexander Geiss (see Appendix D)
- For EARLINET (ACTRIS): monitor alignment and determine height of full overlap with telecover test (Freudenthaler et al. 2018)
- Calibrations as explained in Appendix A where the number of successful calibrations can be used as an indicator of device aging and consequently as indicator for necessary replacements of parts of the device

Some of these QA/QC procedures are already applied within E-PROFILE or Cloudnet/ACTRIS. The advantage is that standardized procedures can be applied to a large number of instruments and thus comparable results can be obtained which is important for homogeneous data in a network. In addition, associated time series of housekeeping data or calibration coefficients are stored, which is required for subsequent processing to level L2 and further analysis.
For example, in E-PROFILE, the Rayleigh calibration is applied on CHM15k and Mini-MPL devices, while the liquid cloud method is used for CL31 and CL51 instruments.
Currently, a full processing chain for ALCs with QA/QC procedures is set-up in ACTRIS by the Centre for Cloud Remote Sensing (CCRES), its corresponding data center (CLU) and experts from the Centre for Aerosol Remote Sensing (CARS). Important housekeeping data parameters and their critical thresholds have been identified by experienced operators and researchers for each ALC model which can be made available on request. ACTRIS developed an application to monitor all the identified

housekeeping data variables (https://ccres.ipsl.fr/docs/services/grafana-server/first-connection.html, login and password is limited to the ACTRIS National Facility PI). The monitored variables will be accessible and visualized through web dashboards and alerts will be sent to instrument operators when HKD parameters exceed or fall below predefined threshold values. This shall allow stations to get the best uptime possible and data with the best quality.

Part 3 Data formats and file standards (D3.1)

The various product levels defined for ALCs are already listed in Table 1 in Part 1. The native data formats of the manufacturers devices differ significantly between the available ALCs in terms of their format (ASCII or netCDF) and content, which can also be seen in the table in the Appendix B. As a guideline, the raw data should first be saved in the manufacturer's format and then processed further. Table 3 lists which formats are accepted or recommended for centralized processing in E-PROFILE or ACTRIS. It is recommended to process Level L0 data with Raw2L1 (see Part 4). This ensures that NetCDF data format is used which follows the Climate and Forecast (CF, https://cfconventions.org/) metadata convention.

Table 3: Native data format of the firmware from different ALC models and the recommendation when data processing should be performed centralized at E-PROFILE or ACTRIS.

Manufacturer	**Raw Format**	**Recommended by**		**Accepted by**	
		E-PROFILE[1]	ACTRIS[2]	E-PROFILE	ACTRIS
Vaisala	ascii (CL31, CL51)	x	x	x	x
	ascii (CL31, CL51)			x	x
	netCDF (CL61)		x		x
Lufft	ASCII			x	x
	NetCDF	x	x	x	x
Raymetrics	Raw data: text header + binary file				
	NetCDF				
Droplet MT	Raw data (text header+binary file), .CSV NetCDF	x	x	x	x
Cimel	Raw data: proprietary binary file Export data: ASCII, PNG (NetCDF)			x	x
Campbell Sci	ASCII		x		

[1] E-PROFILE is part of the EUMETNET Composite Observing System, EUCOS, managing the European networks of e.g. ALC for the monitoring of vertical aerosol profiles.
[2] ACTRIS is the Aerosol, Clouds and Trace Gases Research Infrastructure.

Part 4 Processing algorithms and retrieval codes (D3.3, D4.2)

An overview of available processing algorithms for ALCs is given in [VMG 02]. A few important methods are briefly described below.

Raw2L1 - Data harmonization and standardization

As mentioned in Part 1, Raw2L1 is a code to convert raw data (level L0) from various ALCs into NetCDF format (level L1). The tool was developed in the framework of E-PROFILE and the ToPRof Cost Action ES1303. Raw2L1 produces a standardized and harmonized data/file format with necessary information added which is not provided for all ALCs in the manufacturer's raw data (e.g. instrument settings, overlap function, geolocation information). The NetCDF output follows CF-conventions. Currently, Raw2L1 supports the conversion of following ALCs:

- Vaisala CL31, CL51 and CL61
- Lufft CHM8k and CHM15k(x)
- Campbell Scientific SKYVUEPro (CS135)
- Droplet MT MiniMPL

An overview of the variables of each model available in level L1 is shown in Table 4 in Appendix B.
The tool and its code (Python) is available at Github (https://github.com/ACTRIS-CCRES/raw2l1) and development is still ongoing for further improvements and additional ALC models.

Overlap correction

The manufacturers of most ceilometers provide the overlap function of their devices. Ott Hydromet determines for each ceilometer its individual overlap function. Vaisala claims that their manufacturing process is so stable that all devices of the same type have the same overlap function.
All manufacturers don't provide an uncertainty of the overlap function. Hence it is unknown how accurate this function is and whether it is stable over time or not.
Hervo et al. (2016) developed a method for checking the stability of an overlap function by making assumptions on the atmosphere. It turned out that the overlap function of CHM15k shows a temperature dependency which can be corrected. This was implemented in E-PROFILE by Martin Osborne [VMG 01].
Code is available on Github: https://github.com/martin-obs/OVERLAP_PROBE_EPROFILE

Dark background correction

Lidar signals are affected by different noise sources which can be external (e.g., solar radiation) or internal (e.g., electronic). Solar background noise is a range independent component whereas electronic noise sources are instrument related and result in range dependent signal distortions.
Correcting for such lidar signal distortions is an important step in lidar data processing and usually done for aerosol high-power lidar (AHL) as part of QA/QC procedures (Freudenthaler et. al, 2018). For ALCs, however, only the background signal originating from solar radiation is corrected in the manufacturer's firmware but no correction is applied for dark signal distortions. Within the framework of ACTRIS, the necessity of dark measurements for background correction is currently investigated for different ALC models. For details see Appendix D.

Part 5 References

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Wiegner, M., Madonna, F., Binietoglou, I., Forkel, R., Gasteiger, J., Geiß, A., Pappalardo, G., Schäfer, K., Thomas, W., 2014. What is the benefit of ceilometers for aerosol remote sensing? An answer from EARLINET. Atmospheric Measurement Techniques 7, 1979–1997. https://doi.org/10.5194/amt-7-1979-2014

User manuals
Lufft CHM15k:
https://www.lufft.com/products/cloud-height-snow-depth-sensors-288/ceilometer-chm-15k-nimbus-2300/
Lufft CHM8k:
https://www.lufft.com/products/cloud-height-snow-depth-sensors-288/lufft-ceilometer-chm8k-2405/
Vaisala CL61:
https://www.vaisala.com/en/search?k=cl61&content_group=documents
Vaisala CL31:
(not online and only on paper available)
Vaisala CL51:
(not online and only on paper available)
Campbell Scientific SkyVUEPRO:
https://s.campbellsci.com/documents/us/manuals/skyvuepro.pdf
CIMEL CE376:
https://www.cimel.fr/downloads/#dld-lidars

Appendix A Calibration Methods

Rayleigh Calibration Method

In the Rayleigh calibration method, the measured signal is fitted to a known molecular signal which is calculated from known vertical profiles of molecules (nitrogen, oxygen) in the atmosphere.

Requirements:

- Ceilometer suitable for the Rayleigh calibration method. This is usually a ceilometer which uses photon counting as detection mode
- Clear sky for several hours during night-time
- Preferable: Low aerosol optical depth
- Preferable: Stable atmosphere
- Existence of a layer where aerosol particles are almost absent
- Preferable: knowledge of temperature and pressure profile

<u>Practical considerations and exemplifications</u>

Experience shows that 3-4 hours measurements during a night are sufficient for applying the Rayleigh calibration method provided that the above requirements are met. A clear sky in a stable atmosphere is required because the signal-to-noise ratio after averaging over time is optimal. The low aerosol optical is required for three reasons. First AOD variations over time would reduce the SNR, second a high AOD below the range of calibration would reduce the SNR of the range of calibration and third, the AOD should be corrected in order to yield the calibration value.

The calculated backscattered signal depends on the density or number concentration of nitrogen and oxygen molecules in the atmosphere. These densities can be calculated from profiles of temperature and pressure. The best way of getting temperature and pressure are measurements by radio sondes. However, these soundings are not always available. An alternative way is the use of state-of-the-art weather forecast models. The model outcome is quite accurate for analysis or short-term forecast.

From the theoretical point of view of the Rayleigh calibration, one should use heights above 30 km because only there exists an aerosol free atmosphere. However, ALCs cannot be measured in these regions. Due to the low power and associated low SNR – in practice – one needs to find a region which is almost aerosol free in the middle troposphere. Remaining aerosol particles would contribute to the uncertainty of the calibration value. Fig. X shows an example of the Rayleigh calibration for the lidar Ralph located at Hohenpeissenberg, Germany.

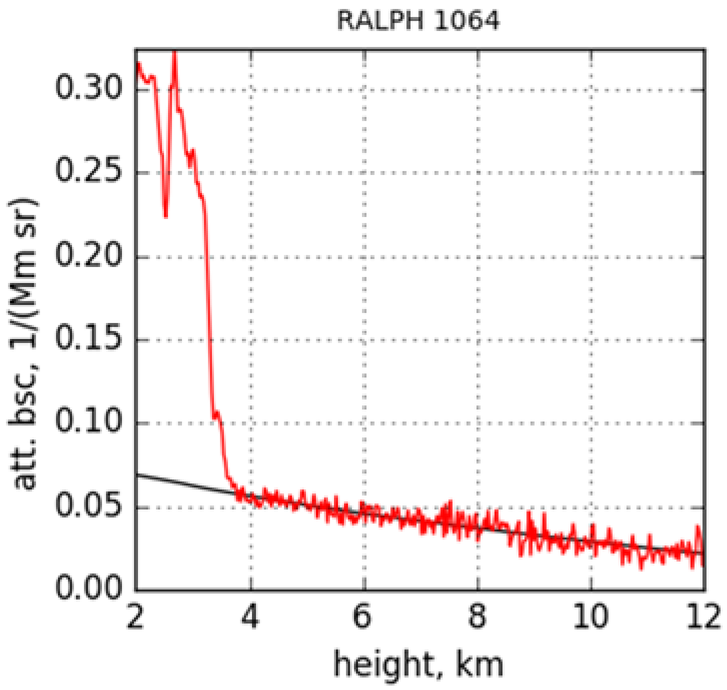

Figure 1: Example of a Rayleigh fit at 1064 nm for the Lidar Ralph located at Hohenpeissenberg. The measurements were done on 13 Sep. 2016. The black curve shows the calculated Rayleigh signal and the red curve shows the measurements fitted between 5 and 10 km to the Rayleigh signal.

Furthermore, it is known for the ceilometers of type CHM15k that the calibration value shows an annual cycle (see Fig. X). The origin of this cycle is currently unknown. Various investigations were done in order to identify whether the annual cycle is caused by changes of the instrument itself or caused by an annual cycle of the aerosol concentration in the free troposphere. As written above, the requirement of an aerosol free region is not fully fulfilled in the troposphere. During the Cost-Action Probe 2 virtual mobility grants were executed which tackled this topic: Buxmann, Joelle (2023) and van Hove, Melania (2023).

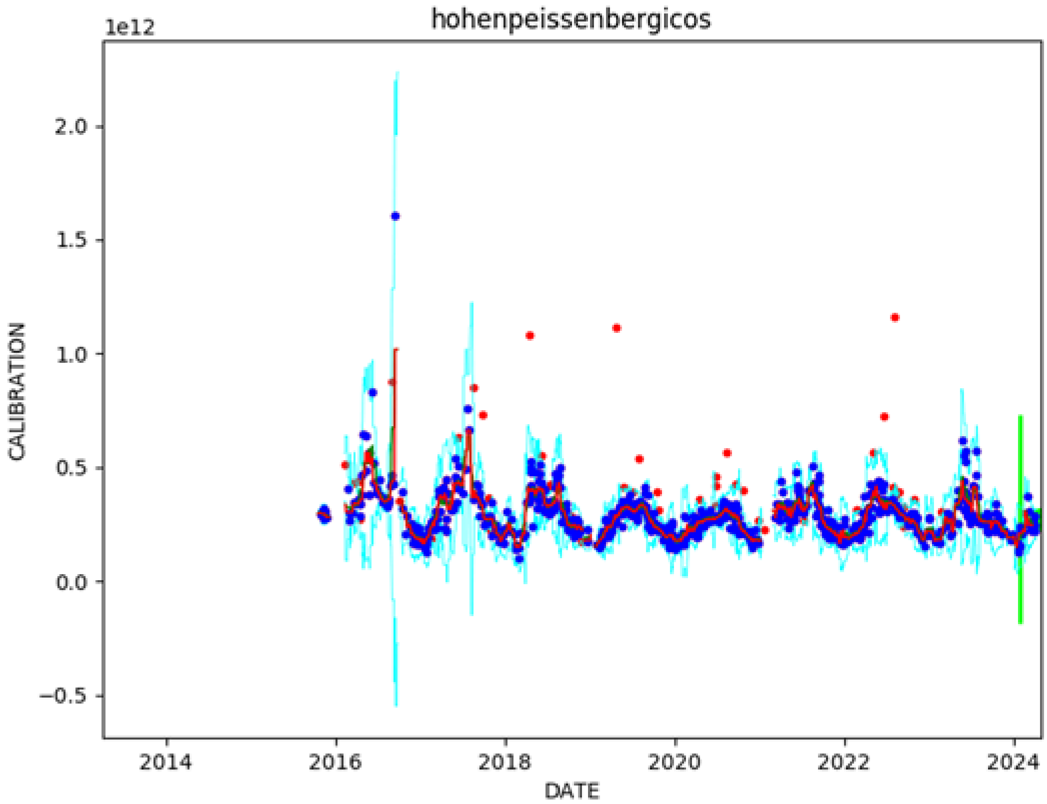

Figure 2: Calibration value of the ceilometer located at the foot of Hohenpeissenberg, Germany. The blue dots correspond to the determined calibration value. The red dots show the values which are considered as outliers. The solid red curve shows a running mean of 1 month and the cyan lines are percentiles and are used to determine outliers.

Cloud Calibration Method

In the cloud calibration method, the measured backscatter signal is integrated over a cloud. This integral equals a constant from which the calibration value of the instrument can be derived.

Equation:

$$C_{Ceilometer} = \frac{1}{2\eta S \int_{Cloud\ Bottom}^{Cloud\ Top} \beta dz}$$

Where: $C_{Ceilometer}$ denotes the calibration values, the backscatter β is integrated between cloud bottom and cloud top and multiplied with a correction factor η which accounts for multiple scattering. S stands for the lidar ratio. It is 18.8 +/- 0.8 sr for a liquid water cloud.

<u>Detailed description of the cloud calibration method</u>

Requirements:

- liquid water clouds
- laser beam is fully attenuated within the cloud
- detector must measure correctly (not go into saturation)

Practical considerations and exemplifications

The check whether a cloud is only liquid or not (mixed phase, ice cloud) can be done through a temperature profile. The best way of getting the temperature profile are measurements by radio sondes. However, these soundings are not always available. An alternative way is the use of state-of-the-art weather forecast models. The model outcome is quite accurate for analysis or short-term forecast.

In case of multiple cloud layers, it is obvious that the laser beam is not fully attenuated inside the lowest cloud layer which is normally the candidate for applying the cloud calibration method. Without multiple cloud layers it is tricky to check for the beam attenuation. Experience tells that normally liquid water clouds which are thicker than 300m will attenuate the laser beam completely.

It is well known that photon counting detectors go into saturation when the received number of photons is too high. It is also well known that for devices of type CHM15k such a saturation can be detected or identified with a so-called undershooting. This is a negative signal above the cloud base height.

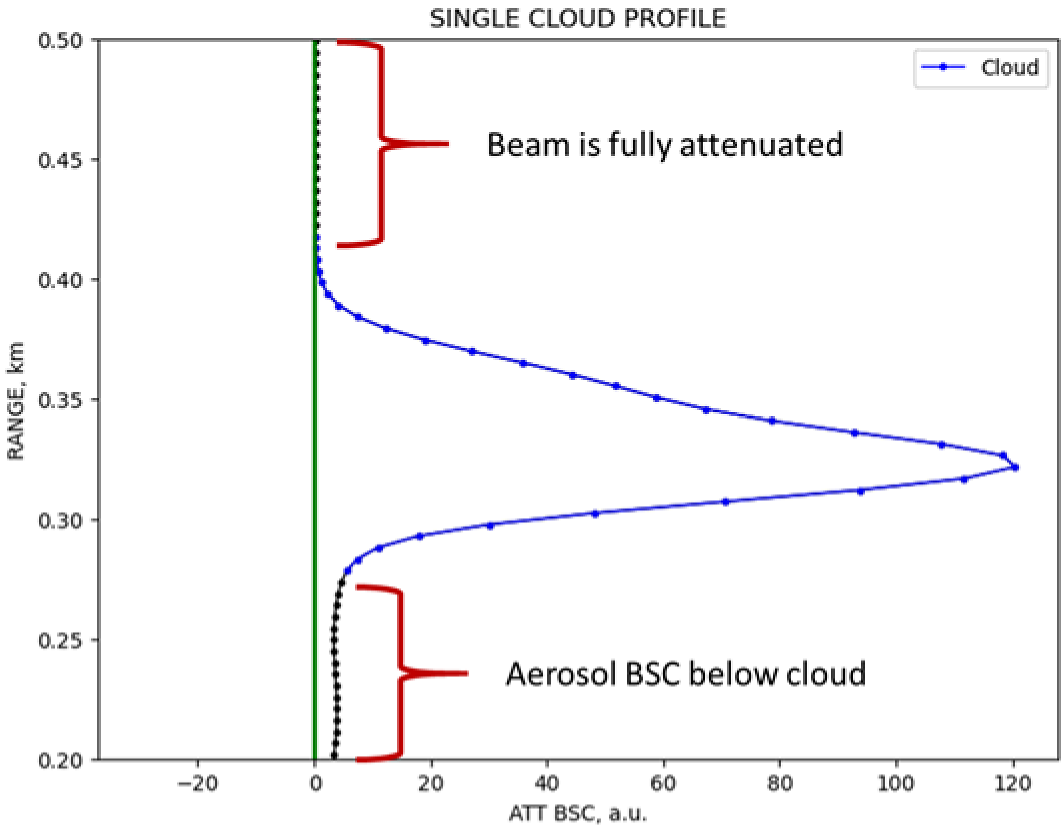

Figure 3: Illustration on the cloud calibration method.

Depolarization

Calibration procedures that could be employed by Ceilometers to optimize the polarization channels:

Polarization channel calibration is tailored to individual lidar and ceilometer systems, although the underlying principles remain largely uniform across most instruments. This calibration process involves evaluating the measured calibration factor and subsequently implementing any required adjustments to minimize instrument-related contributions.

To determine the measured calibration factor, one initial method involves employing either the 0-degree calibration or the atmospheric calibration. With this approach, the system's impact on the ultimate lidar depolarization outcomes is evaluated by analyzing a low aerosol altitude range within the lidar signal, where predominantly molecular contributions are assumed. Within this atmospheric

domain, the total volume linear depolarization ratio can be approximated using the established value of the air molecular linear depolarization ratio.
Typically, this process may introduce additional uncertainties, as it necessitates at least two reference points for accurate calibration. Furthermore, a drawback arises from the presence of trace amounts of highly depolarizing aerosols (such as ice crystals) within the presumed clean range, which can easily result in significant errors in depolarization products (Freudenthaler et al., 2009; Freudenthaler, 2016). Alternative calibration techniques include utilizing depolarization optics in the receiver to calibrate the lidar gain ratio (Winker et al., 2007), or employing three lidar signals (cross, parallel, and total) for calibrating depolarization products. The three-lidar signals method involves utilizing two altitude ranges – one with high depolarization and the other with low depolarization load – to derive the calibration constant for the calibration channels.

A reliable method for calibrating depolarization measurements involves employing the 45-degree calibration technique. This method entails rotating the depolarization analyzer, composed of the Polarisation Separation Unit (PSU) and Photomultiplier Tubes (PMTs), by 45 degrees concerning the laser's polarization plane. This rotation aims to ensure uniform light intensity across both the cross and parallel channels. By comparing the calibration signals, the ratio between transmitted and reflected signals reveals the influence of optics and electronics within the lidar receiving unit. However, the primary challenge with this calibration method lies in achieving precise accuracy, particularly in executing the 45-degree rotation relative to the PSU's true zero position.
A more reliable approach involves conducting two consecutive measurements by rotating the depolarization analyzer by 45 degrees relative to the default measuring position (David, et al., 2012). This calibration method, known as the "45-degree calibration," determines the calibration constant by utilizing the geometric mean of these two 45-degree measurements. The purpose of employing two measurements is to offset any uncertainties arising from large rotation errors of 45 degrees concerning the initial zero position provided by the Polarisation Separation Unit (PSU) (Freudenthaler et al., 2009).
Given that the initial zero position reference holds less significance for the 45-degree calibration, a more generalized approach involves conducting two consecutive measurements with an exact 90-degree difference in the rotation of the depolarization analyzer. This calibration technique, termed the "delta 90-degree calibration," yields results similar to those obtained from the 45-degree calibration. The 45-degree calibration can be viewed as a specific instance of the delta 90-degree rotation calibration, as the only requirement for this calibration is the 90-degree angle between the two measurements.
The delta 90-degree calibration can be technically executed by employing a mechanical rotator (holder) capable of fixed rotations at delta 90 degrees for the optical components. This device is termed the "delta 90-degree mechanical rotation calibrator." Alternatively, a similar outcome can be achieved by utilizing a half-wave plate (HWP) to precisely rotate the emitted or collected light by delta 90 degrees. An advantage of this approach is that while the mechanical rotator is restricted to placement within the reception unit (either in front of the receiving optics or in front of the Polarisation Separation Unit), the HWP module can be positioned at both the emission stage, before and after the emission optics. This device is referred to as the " delta 90-degree HWP calibrator."
Another method for implementing the delta 90-degree calibration involves incorporating an additional linear polarizer capable of fixed rotations at delta 90 degrees. In this scenario, the delta 90-degree rotation is substituted with the presence of the supplementary linear polarizer. Depending on its location within the optical chain (whether in front of the telescope, receiving optics, or the

Polarization Separation Unit), this calibration can account for all lidar optics situated after the polarizer, such as the receiving optics, Polarization Separation Unit, and Photomultiplier Tubes (PMTs).

The most straightforward approach is to utilize the Half-Wave Plate (HWP) due to its dual functionality: firstly, it facilitates the initial adjustment of the laser's plane of polarization concerning the Polarization Separation Unit of the analyzer, and secondly, it enables the actual rotation by adjusting the plane of polarization at ±45 degrees. This solution is particularly advantageous for ceilometer instruments, which typically operate with a single wavelength. Implementing the HWP in front of the entire receiving unit ensures minimal interference with other channels that may be measuring at different wavelengths. This approach enables the calibrator to characterize the entirety of the receiving unit, rather than solely addressing the effects of hardware after the Polarization Separation Unit.

When it comes to the Raymetrics Ceilometer instrument, polarization calibration involves employing an automatic rotation mount and a first-order HWP unit (https://raymetrics.com/3d-ceilometer/). This unit can function in an operational mode because the position of the HWP is electronically regulated and synchronized for specific durations.

Instrument specific calibration information

- Campbell Sci SkyVUE series has a built-in cloud calibration option for on-site absolute calibration.
- Vaisala CL61 attenuated backscatter profiles are calibrated against a reference instrument that was calibrated at factory using the cloud calibration method (O'Conner et al., 2004). Also on-site recalibration is possible. CL61 also has SI traceable calibration certificate for time-of-flight measurement.
- Recently, Lufft/OttHydromet introduced a new NetCDF format with firmware 1.050 for CHM15k devices which provides factory calibrated attenuated backscatter (2020). Older firmware versions just deliver range-corrected signals.

Appendix B Data Harmonization and Standardization

For further processing to higher product levels or for future assimilation of measurements in numerical weather prediction models, it is important that the measurement data is harmonized and standardized. This is already realized with the [Raw2L1](Raw2L1) tool for several ALC models with the processing from level L0 to L1. As the raw output of the individual models differs in the number of variables, not all parameters are available for each model in level L1 format, as shown in Table 1. It should be noted that the variable names may change with the further development of Raw2L1 and new parameters may also be added as a result of firmware updates.

Table 4: List of variables in level L1 format for different ALC models after processing with Raw2L1.

Variable		Description	CHM 15K	CHM 8k	CL31	CL51	CL61	Mini-MPL	SkyVUEPRO
Dimensions	time	End time (UTC) of the measurements							
	range	Distance from lidar							
	layer	number of cloud layers retrieved							
	layer_aerosol	number of aerosol layers retrieved							
	layer_mlh	Index of mixing layer height							
	range_raw	range from instrument							
	range_vbp	range from backscatter							
Housekeeping data	start_time	Start time (UTC) of the measurements							
	temperature_laser	Temperature of the laser							
	temperature_optical_module	Temperature of the laser optic module							
	temperature_detector	Detector temperature							
	temp_transmitter	Transmitter enclosure temperature (hot side of laser peltier)							
	temp_int	Internal temperature							
	temp_ext	External temperature							
	status_detector	quality of detector signal							
	status_laser	Laser quality index in							

		percent							
	calibration_pulse	Calibration pulse in photons per shot							
	laser_life_time	laser life time, operating hours							
	laser_pulses	Number of laser pulse per record							
	laser_energy	laser pulse energy, percent of nominal factory setting							
	laser_power	Laser output power							
	error_string	status code							
	status_codes	Several status variables							
	average_time	average time per record							
	time_resol	temporal resolution							
	rh_int	Internal relative humidity							
	pres_int	internal pressure							
	window_transmission	Window transmission estimate							
	background_radiance	sky background radiance at the receiver FOV							
	heater_int	Internal heater (on/off)							
	window_blower	Window blower (on/off)							
	window_blower_heater	Window blower heater (on/off)							
Atmosphericalparameters	cloud_base_height	cloud base height							
	cloud_amount	cloud cover in eights							
	rcs_0	Total normalised range corrected signal							
	rcs_1	Co-polarised normalised range corrected signal							
	rcs_2	Cross-polarised normalised range corrected signal							
	volume_ldr	Volume linear depolarisation ratio							
	sum_rcs0	sum of detected and normalised backscatter							

	stddev	standard deviation of raw signal							
	backgrd_rcs_0	baseline raw signal							
	cdp	Cloud penetration depth							
	cde	Cloud penetration depth variation							
	cbe	Cloud base height variation							
	clh	Cloud layer height							
	tcc	Total cloud cover							
	cloud_altitude_maximum_intensity	Cloud altitude maximum intensity							
	cloud_highest_altitude_detected	Cloud highest altitude detected							
	pbl	Planetary Boundary Layer height							
	pbs	PBL quality score							
	aod	Atmosphere Absorption Optical Thickness							
	vertical_visibility	Vertical visibility or optical range							
	vertical_visibility_error	Vertical visibility error							
	ext_coeff	Extinction coefficient							
	mass_concentration	Mass concentration							
	particle_type	Type of Particle							
	raw_signal_1	Raw Signal Parallel							
	raw_signal_2	Raw Signal Cross							
	snr_1	Signal Noise Ratio Parallel							
	snr_2	Signal Noise Ratio Cross							
	vbp_coeff	Vertical Backscatter Coefficient							
	sci	Sky Condition Index							
Location and instrument settings	station_latitude	Latitude of measurement station							
	station_longit	Longitude of							

	ude	measurement station							
	station_altitude	Altitude of measurement station							
	alt	Altitude							
	lat	Latitude							
	lon	Longitude							
	tilt_angle	Instrument tilt angle from vertical							
	azimuth_angle	Azimuth angle of the pointing direction of the laser on site							
	lidar_ratio	Lidar Ratio							
	depolarization_ratio	Volume Depolarization Ratio							
	range_resol	Range resolution							
	time_resol	Time resolution							
	t0_fov	Telescope 0 Field of View							
Laser	l0_beam_div	Laser 0 Beam Divergence							
	l0_prf	Laser 0 Pulse Repetition Frequency							
	l0_wavelength	Laser 0 Wavelength							
	l0_width	Laser 0 Line Width							

Appendix C Overlap Functions

Overlap Functions

In the near range, a ceilometer receives less backscattered light due to the incomplete overlap between laser beam and field-of-view of the telescope.

The manufacturers normally provide overlap functions for their systems.

Fig. 4 shows the overlap functions of 7 ceilometers between ground and 1000m distance.

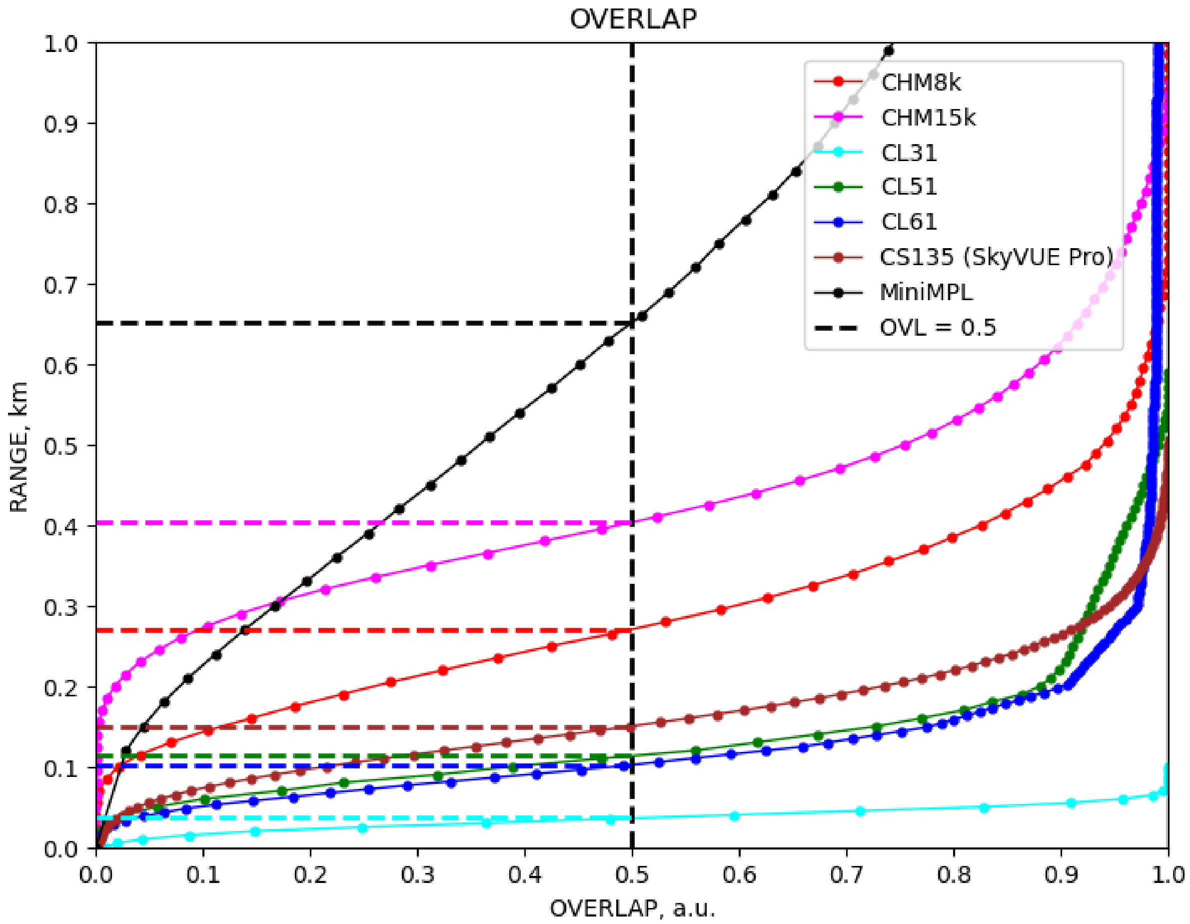

Figure 4: Overlap function of different ALCs. The dashed lines show the range of the 50%-overlap.

Fig. 5 shows the same overlap functions as above but with a focus on the blind zone. The blind zone was defined (see Table 2, Part 1) as the region where the function has a value smaller than 3%.

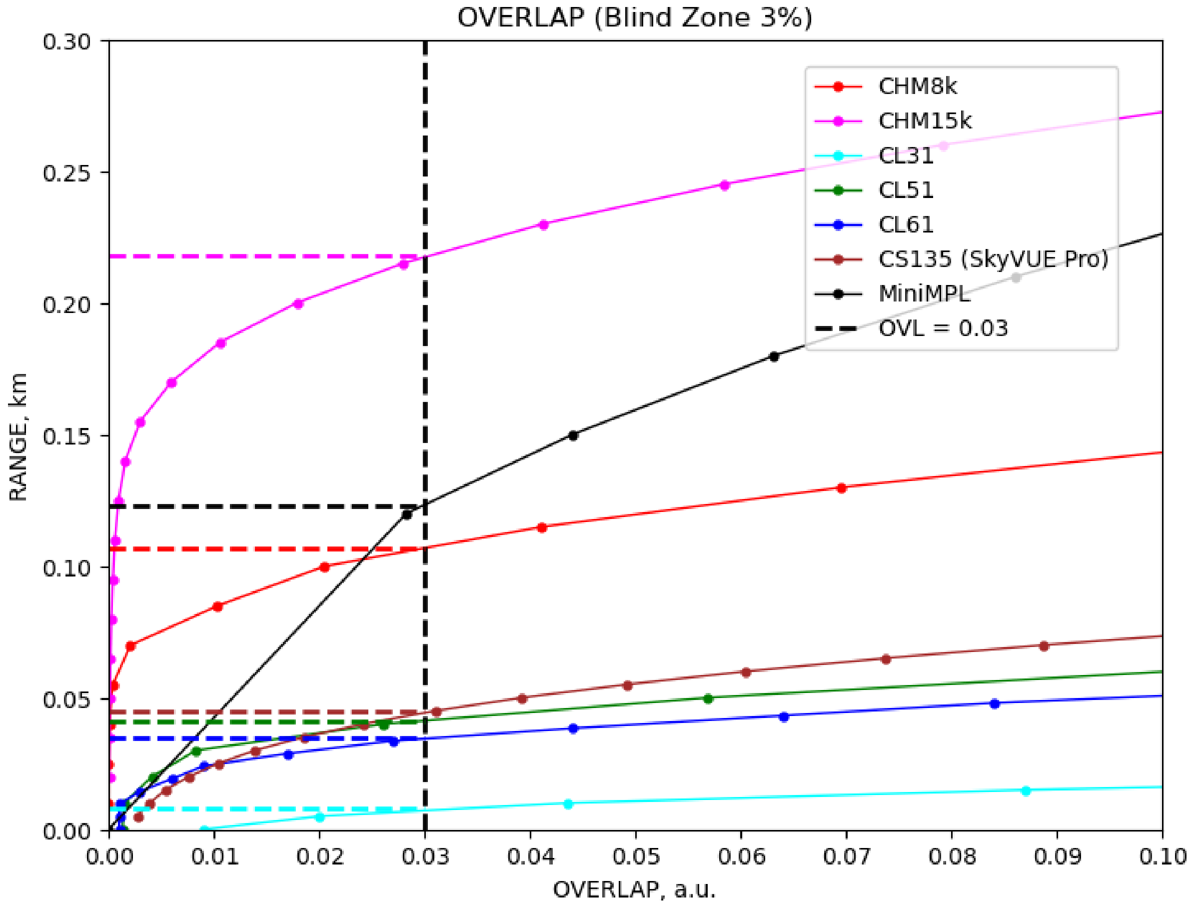

Figure 5: Illustration of the blind zone defined with a 3% threshold of the overlap function. The dashed lines show the range of the blind zone.

Appendix D Instrument related background - Dark signal

Lidar signals are affected by different noise sources which can be external (e.g., solar radiation) or internal (e.g., electronic). Solar background noise is a range independent component whereas electronic noise sources are instrument related and result in range dependent signal distortions.
Correcting for such lidar signal distortions is an important step in lidar data processing and usually done for aerosol high-power lidar (AHL) as part of QA/QC procedures (Freudenthaler et. al, 2018). For ALCs, however, only the background signal originating from solar radiation is corrected in the manufacturer's firmware but no correction is applied for dark signal distortions. Within the framework of ACTRIS, the necessity of dark measurements for background correction is currently investigated for different ALC models.

For conducting dark measurements with monostatic systems (e.g. Vaisala CL31, CL51, CL61) the manufacturer provides a so-called optical termination hood (see Fig. 6, left) as an optional part for indoor service. This conical cylinder is built in a way to fully extinguish the outgoing laser beam in order to measure only the remaining dark signal.
For bistatic systems (e.g. Lufft CHM15k or CHM8k) the optical axes of the laser and telescope are divided and a simple black cardboard can be used to cover the telescope to suppress the atmospheric backscatter signal (see Fig. 6, right).

Figure 6: Vaisala CL31 (monostatic) with optical termination hood (left) and laser optical module (LOM) of Lufft CHM15kx (bistatic) with cardboard covering the telescope (right) from the ACTRIS CARS ALC unit testbed.

The ACTRIS CARS ALC units at Ludwig-Maximilians-Universität in Munich and at Deutscher Wetterdienst Hohenpeißenberg are operating a testbed with ALC models from different manufacturers. In order to characterize the systems, dark measurements are performed one or two times per month. In Fig. 7, the profiles of the measurements from a Vaisala CL31, CL51, CL61, Campbell Scientific SKYVUEPro, two Lufft CHM8k and a Lufft CHM15kx are shown. Ideally, the signal should vary around zero to have no influence on the atmospheric measurements. However, as can be seen from the strongly fluctuating profiles of some devices, this is not always the case. Consequently, to improve data quality especially for aerosol profiling, a dark background correction might be necessary. Whether this is needed for all models and what a possible correction with additional dark measurements should look like in operational networks is the subject of current investigations in ACTRIS.

A first statistical approach was developed and analyzed by Kotthaus et. al, 2016, for the Vaisala CL31 model. However, this assumes a low variability of the dark measurements, which is not necessarily the case for all models.

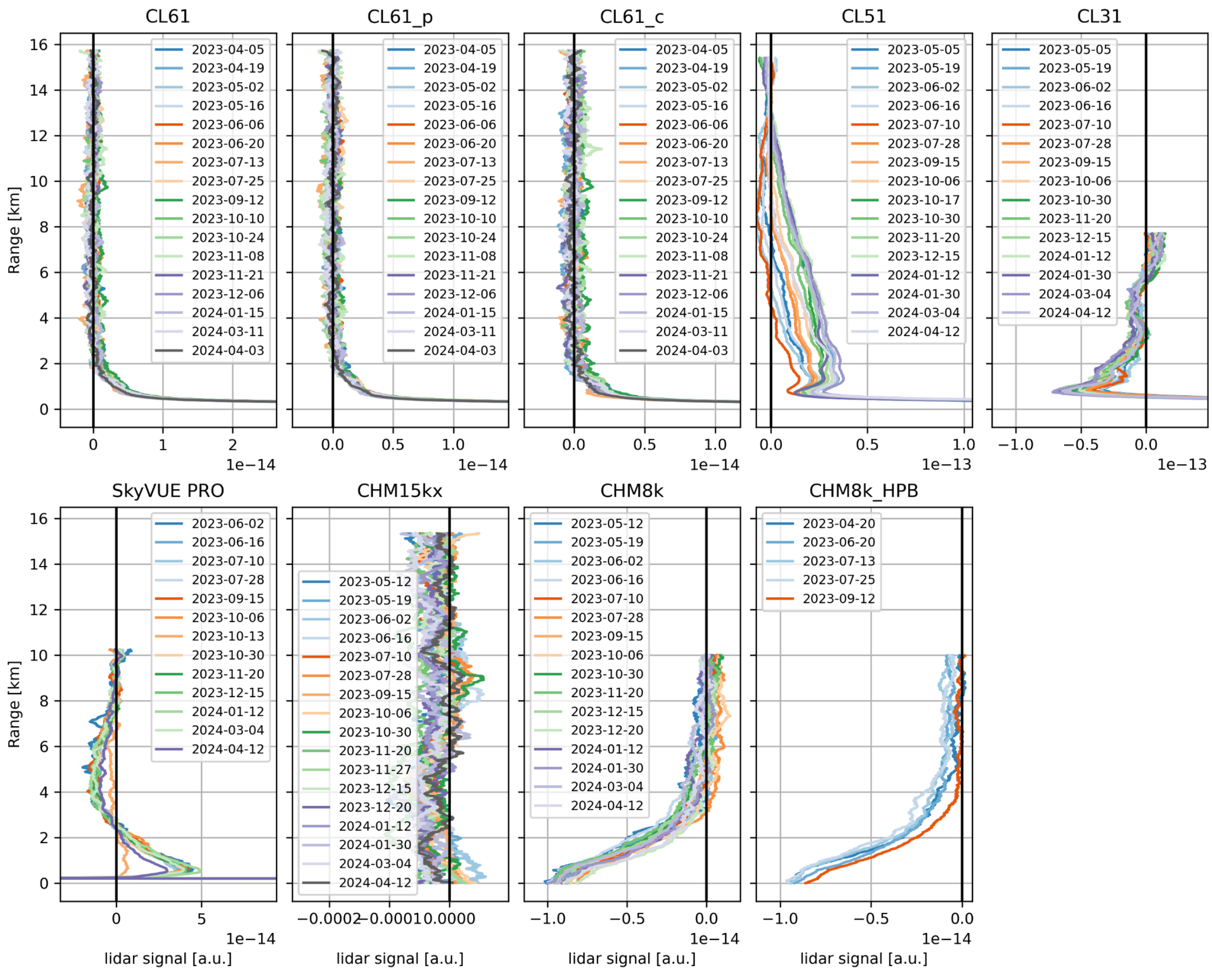

Figure 7: Profiles of dark measurements from various dates from ALCs operated in the ACTRIS CARS ALC unit testbed. The overlap correction and range correction was removed.

Appendix E Cloud base height

The firmware of the manufacturer determines the height of a cloud. Due to different definitions and hence different algorithms, these heights differ for the same cloud. Fig. 8 and 9 show an example for low clouds over the Hohenpeissenberg and Munich ACTRIS testbeds. One can see that the ceilometers manufactured by OttHydromet (CHM15k, CHM8k) and Campbell (CS135) provide the cloud base height near the bottom of a cloud. Whereas the ceilometers manufactured by Vaisala (CL31, CL51, CL61) provide the cloud base height slightly above the maximum of the signal. The MiniMPL software provides cloud base height values approx. 100 m below the cloud base height (CBH) derived by the other ALCs. The reason is likely a different definition of the CBH.

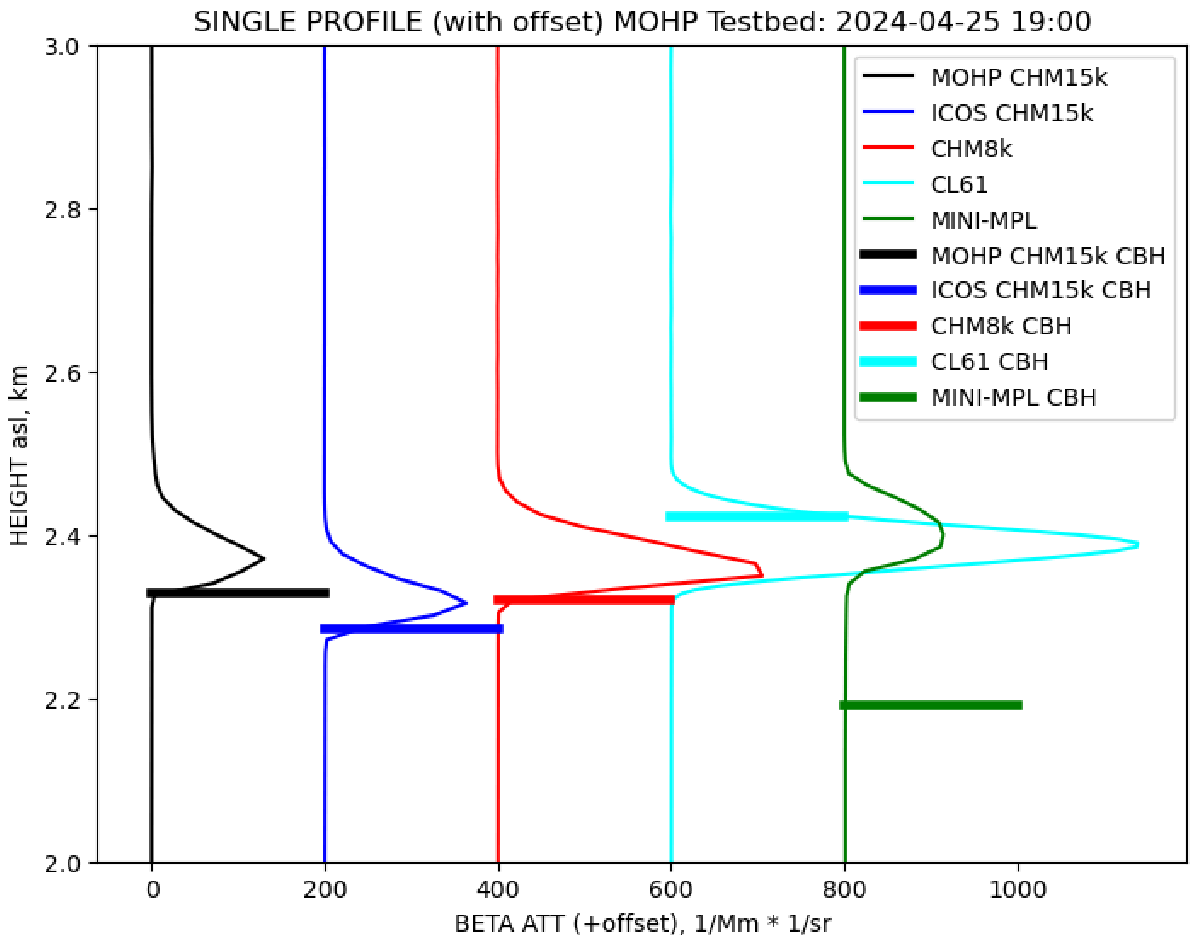

Figure 8: Profiles of the attenuated backscatter and the cloud base height as determined by the manufacturers software at MOHP Hohenpeissenberg ACTRIS testbed. For better visualization, an offset was added to each attenuated backscatter profile.

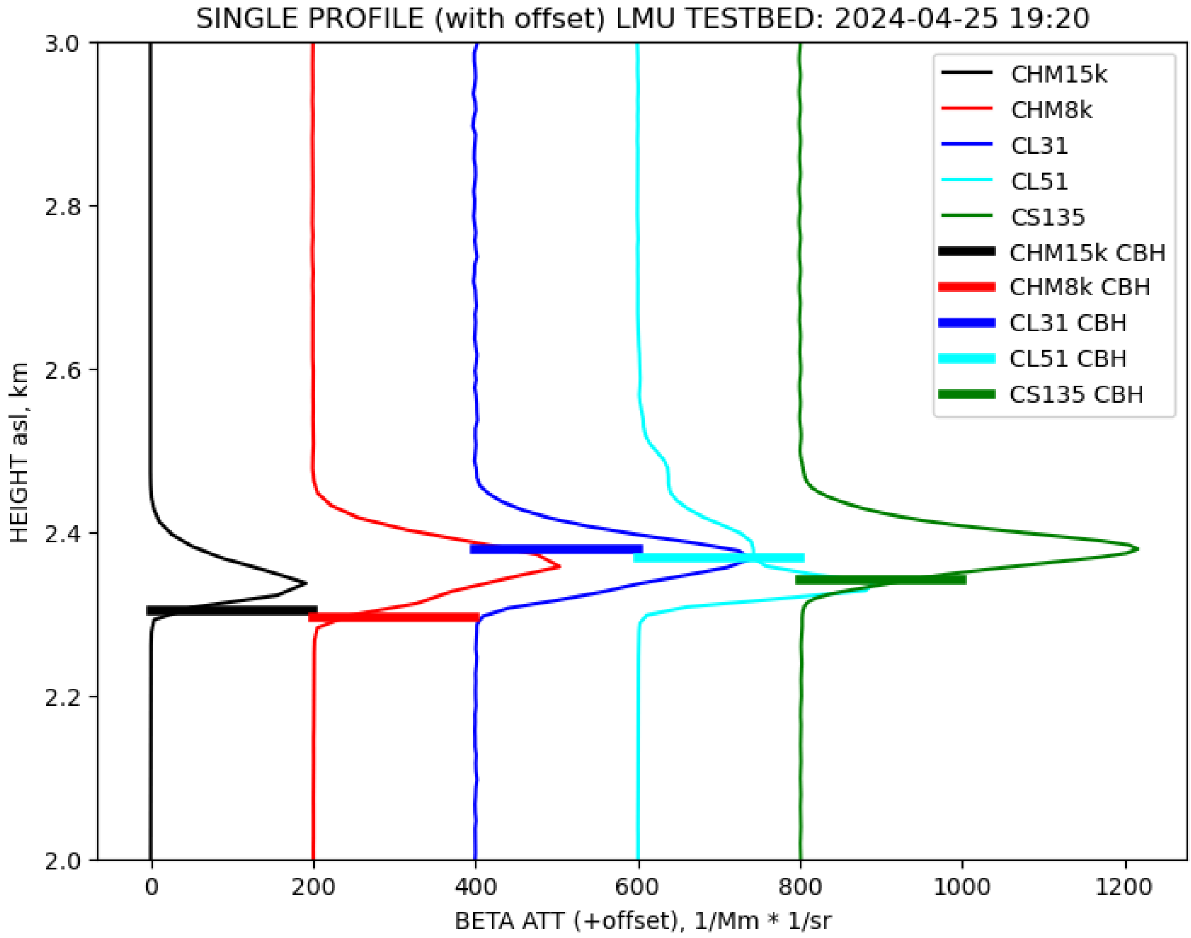

Figure 9: Profiles of the attenuated backscatter and the cloud base height as determined by the manufacturers software at LMU Munich ACTRIS testbed. For better visualization, an offset was added to each attenuated backscatter profile.