The ceilometer inter-comparison campaign CeiLinEx2015 - Cloud detection and cloud base height -

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Abstract. Ceilometers are well established standard instruments in the Meteorological Services for the detection and estimation of cloud base heights. During the last years, ceilometer intensity profiles have been also used for retrieving aerosol volume backscatter profiles, to derive mixing layer heights or to identify elevated aerosol layers caused e.g. by volcanic ash. In the framework of the European projects EUMETNET E-PROFILE and COST TOPROF efforts are being made for an exchange of harmonized ceilometer data among the European Meteorological Services. This requires the development of tools for the standardization of data formats, the calibration and visualization of ceilometer data. Since different ceilometer types are in use, an intercomparison campaign has been carried out at the Meteorological Observatory Lindenberg (Deutscher Wetterdienst) from June to September 2015, where six different ceilometer types (LUFFT CHM15k, CHM15kx; Vaisala LD40, CL31, CL51 and Campbell CS135) have been operated side-by-side. Each ceilometer type was represented by two instruments to get an idea about the instrument-to-instrument variability. In this contribution the results concerning cloud detection and cloud base height estimation are presented. Especially, low clouds have a high relevance for aviation and were therefore in the focus of the comparison. Due to the different technical characteristics of the various ceilometers and a lack of an internationally agreed quantitative definition of cloud base height, cloud reports differ significantly between the different ceilometer types. Even for water clouds height differences of up to 60 m could be observed while during strong rain differences of several hundred meters occurred. The detection rate is comparable for most cloud conditions. Only a few cases (e.g. very wet boundary layer) were found in which some systems erroneously detected clouds in clear conditions.

1 Introduction

For all instruments the comparability of measured and derived quantities is of particular importance. Intercomparisons are a common method to analyse differences between the different instruments. In the case of ceilometers, intercomparisons are also one the main method to study their performance because of a lack of absolute reference values (see CIMO guide)

Due to the intention to establish an European ceilometer network to obtain aerosol parameters in the framework of the projects E-PROFILE and COST TOPROF the Meteorological Observatory Hohenpeißenberg initiated the ceilometer-intercomparison campaign CeiLinEx2015 and organized together with the Meteorological Observatory Lindenberg, where the experiment took place in summer 2015 (see also Pattantyus-Abraham, 2016). Several institutions have supported the campaign by providing instruments and/or by participation on data analysis to different aspects of the comparison.

The main goals of the campaign were:

– to study the systematic differences and uncertainties for the quantitative determination of attenuated backscatter profiles,

– to study the variations between systems of the same type and between different firmware-versions, respectively,

– to apply and to evaluate different calibration methods

– to investigate different algorithms for mixing layer heights

– to assess the cloud detection capability and to compare cloud base heights (CBH), especially for low clouds

The CBH is still one of the main parameter of ceilometers and plays an important role in aviation. The trend towards unmanned stations requires (even more than in the past) reliable and accurate information about existing clouds and their CBH for the automatic generation of synoptical and aeronautical cloud reports. Due to different technical characteristics of the ceilometers (e.g. transmitting power, optical design), non existing calibration, and different algorithms for the derivation of CBH from backscatter profiles, differences in cloud detection and CBH estimation are to be expected between the various ceilometer types as it was already demonstrated during the last ceilometer-intercomparison campaign initiated by the WMO 30 years ago (Jones et al., 1988) as well as by several individual comparisons (Martucci et al., 2010).

CeiLinEX2015 includes ceilometers which are currently on the market and will therefore provide an actual assessment of their performance.

2 Experimental setup

The campaign CeiLinEx2015 (CEIlometer LINdenberg EXperiment 2015) took place from 1 June until 14 September 2015. The following ceilometers types were involved: LD40 (Vaisala), CHM15k and CHM15kx (Lufft), CL31 (Vaisala), CL51 (Vaisala) and CS135 (Campbell). To study the instrument-to-instrument variability two ceilometers of each type were operated. The location of systems was a compromise to prevent interferences between the ceilometers and the given technical infrastructure. Distances between the instruments ranges from about 10 m to 400 m (s. Fig. 1). A few technical characteristics and the operation parameters used during the campaign are summarized in Table 1.

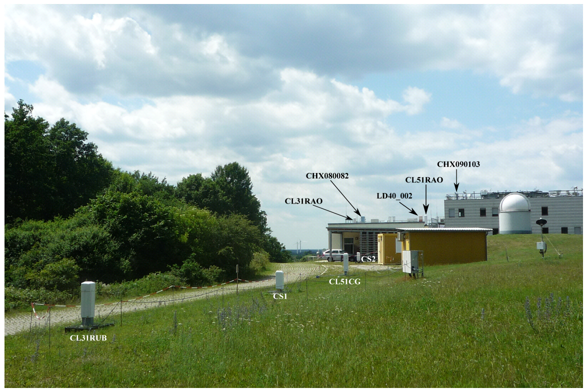

Figure 1. View of the ceilometer test bed. Two systems (CHM15k(A) and LD40(A) are in in a distance of about 400 m)

Uncalibrated attenuated backscatter profiles of all systems as well as firmware derived quantities (e.g. CBH) were stored. Vaisala and Campbell systems provide ASCII data, which were converted into a Netcdf format using the raw2l1-software package provided (http://www.lmd.polytechnique.fr/ strat/)). Furthermore, variable names has been harmonized. The conversion of Lufft ceilometer data was not necessary because these systems already provide netcdf-format as standard output. All data were stored on a central server accessible by all participants. For monitoring purposes, quicklooks of essential parameters were created from all systems and published daily on www.ceilinex2015.de. This web page were also used for documentation (logbook) and brief preliminary discussions and presentation of results.

3 Results

An example of CBH comparison is given in Fig. 2 for a well defined water cloud. Maximum CBH differences of 70 m between CHM15k (lowest) and CL31 (highest) can be observed. The standard deviation is comparable, and the detection rate is 100% for all systems. The mean backscatter profiles for the indicated 10 min period - plotted in Fig. 3 - show a similar shape with height differences of the signal maximum of 30 to 40 m, which cannot explain the CBH differences completely. One of the main source for CBH differences are the different algorithms developed by the manufacturer to derive the CBH. The CBH is analysed at different regions of the backscatter profile. Note, that the backscatter

Ceilometer type	Owner	Laser	Optical design	Height range	Tempor. res.	Vert. res
LD40 A/B	DWD	InGaAs 855 nm	biaxial	0 - 15327 m	15 s	7.5 m
CHM15k A	DWD	Nd: YAG 1064nm	biaxial	5 - 15 000 m	15 s	15 m
CHM15k B	DWD	Nd: YAG 1064nm	biaxial	5 - 15 000 m	15 s	15 m
CHM15kx A	DWD	Nd: YAG 1064nm	biaxial	5 - 15 000 m	15 s	15 m
CHM15kx B	LMU Munich	Nd: YAG 1064nm	biaxial	5 - 15 000 m	15 s	15 m
CL31 A	DWD	InGaAs 910 nm	coaxial	0 - 7600 m	15 s	5 m
CL31 B	RU Bochum	InGaAs 910 nm	coaxial	0 - 7600 m	15 s	5 m
CL51 A	DWD	InGaAs 910 nm	coaxial	0 - 13000 m	15 s	10 m
CL51 B	CAS	InGaAs 910 nm	coaxial	0 - 13000 m	15 s	10 m
CS135 A	Campbell	InGaAs 905 nm	biaxial split-lense	0 - 10000 m	10 s	5(10) m
CS135 B	Campbell	InGaAs 905 nm	biaxial split-lense	0 - 10000 m	10 s	5(10) m

Table 1. Some technical characteristics and operation parameters of the involved ceilometers. A and B is the indicator to separate between systems of the same type. Note, that CHM15k A is inclined by 5

profiles were adjusted to an common profile using a coefficient determined at the beginning of the campaign in the cloud-free atmosphere.

To analyse the performance of each ceilometer in relation to others the following parameters have been calculated for different meteorological situations and cloud types, respectively: the cloud detection rate (number of detected clouds related to the number of measurements), the CBH differences to a common mean (median) and the root mean square differences (RMSD) of CBH between systems of the same type. In order to get representative results periods of the same cloud types as stratocumulus, stratus without and with rain, and fog with possibly high cloud cover were combined. It must be emphasized that no independent reference or standard exists neither of the presence of clouds or for their cloud base height. Only for evaluating false alarm rates some additional instruments (e.g. all sky camera) were used. Only periods where all systems provided reliable data were taken into account. The RMSD to study the instrument-to-instrument variability is based on 10 min means of CBH in order to minimize effects of spatial separation of systems. Table 2 summarises the statistical parameters. It should be noted again, that all statistical parameters can be interpreted only relative to the values of the other system and allow no statement which system is closer to the true values.

It can be seen that the spread of **CBH differences** varies between 41 m for stratus without rain and 71 m for Stratocumulus whereby the deviation to the common mean of CHM15k CBHs are general negative and of CL31/CL51 are positive. In heavy rain CBH differences of several kilometer were observed (e.g. Fig. 4).

The mean **detection rate** varies for Stratocumulus between 68 and 78.1 $\%$. Remarkable is the difference between CHM15k A and B, which is probably caused by the 5 degrees tilt of system A. Furthermore, the detection rate of CHM15kx B is significantly lower than the values of other systems which can currently not be explained. But, one has to keep in mind that the CHM15k x-version was optimized for mixing layer and aerosol studies. The detection rates of systems shows similar small differences also for the other cloud types, except for the CHM15kx B.

To analyse the **false alarm rate** is much more difficult, since unambiguously decisions about cloudless sky are hardly possible in certain situations as for example in fog or heavy haze. Fig. 5 shows an example, where some systems erroneously detect clouds in a very wet boundary layer (relative humidity $> 95\%$ below 40 m). The human observer as well as the sky camera confirm the cloudless sky. The CS135 has erroneously interpreted aerosol layers as clouds in few situations during night.

The **instrument-to-instrument variability** - described by the root mean square differences (RMSD) of CBH - is comparable between the systems for Stratocumulus and Stratus, whereas higher values occur for CHM15k and LD40 during rain.

4 Conclusions

The comparison campaign CeiLInEx2015 provided important insights into the performance of different ceilometer types. Concerning cloud base heights systematic differences of up to 70 m have been observed between the tested systems, which may be important for aviation in situations with low clouds ($<$ 500 m). Due to a lack of an internationally agreed quantitative definition of CBH and a suitable reference an absolute validation of ceilometer derived CBH is currently not possible.

Concerning the detection rate as well as false alarm rate the different ceilometers show a comparable performance. Only in few situations (wet boundary layer, distinctive aerosol layer) clouds were detected erroneously by some systems.

More work is required to investigate the performance of ceilometers in view of diverse technical concepts (e.g. overlap of laser beam and field of view of the receiver) for the

parameter	CHM15k (A/B)	CHM15kx (A/B)	CL31 (A/B)	CL51 (A/B)	CS135 (A/B)	LD40 (A/B)
Sc						
Tot. obs. time, min			2470			
Mean deviation,m	-38.4/-40.0	-32.7/-32.7	29.3/28.6	31.1/30.0	-0.9/-2.1	2.0/11.2
Detection Rate, %	78.1/74.0	75.1/68.0	77.5/76.4	77.2/76.8	76.5/76.7	75.6/76.7
RMSD, m	16.1	11.0	12.0	11.1	11.7	34.5
St w/o rain						
Tot. obs. time, min			760			
Mean deviation,m	-26.6/-24.5	-20.8/29.1	12.2/10.5	16.4/15.2	-5.7/-7.7	0.8/13.8
Detection Rate, %	96.3/96.3	96.5/15.5	96.6/96.3	96.3/96.0	95.0/95.6	96.2/96.2
RMSD, m	11.5	58.4	7.5	6.1	3.7	18.3
St with rain						
Tot. obs. time, min			680			
Mean deviation,m	-31.0/-26.1	-16.9/-4.8	7.55/4.01	11.5/12.2	3.7/-6.42	6.0/29.4
Detection Rate, %	81.1/80.1	85.5/42.9	79.9/79.9	79.7/79.0	76.7/78.5	77.8/75.9
RMSD, m	47.1	65.8	17.3	18.8	16.9	46.1
Fog						
Sampling period			590			
Mean deviation,m	-29.3/-22.8	-17.8/-13.8	20.1/15.7	12.9/6.3	33.0/35.7	-16.2/-6.5
Detection Rate, %	90.0/88.3	88.0/88.2	89.6/90.5	89.8/88.6	78.0/78.0	86.2/86.1
RMSD, m	12.3	8.6	8.8	16.0	11.9	15.1

Table 2. Statistical parameters of intercomparison summarized for the entire period of campaign and separated for different cloud types.

detection of low clouds. Also a standardized algorithm for CBH determination which is optimized for each application would help to harmonize ceilometer networks.

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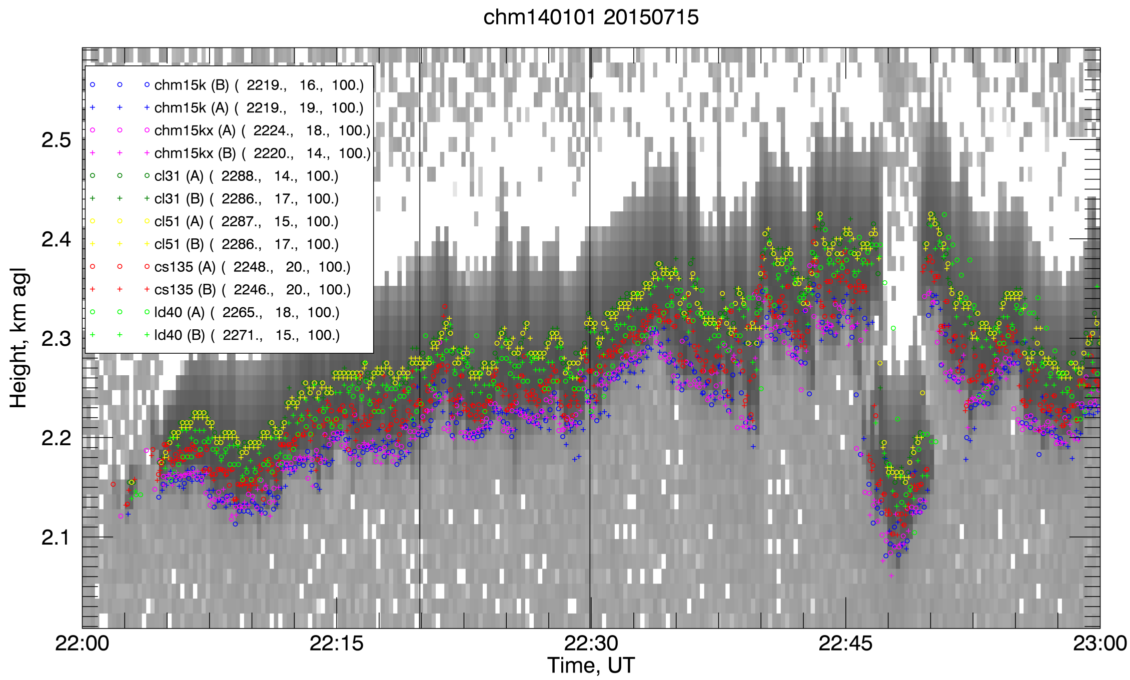

Figure 2. Time-height cross section of $beta_{att}$ (CHM15k-B) and CBH time series of all ceilometers for Stratocumulus, the brackets in the inset contain the mean and standard deviation of CBH and the detection rate for a period marked by the vertical lines.

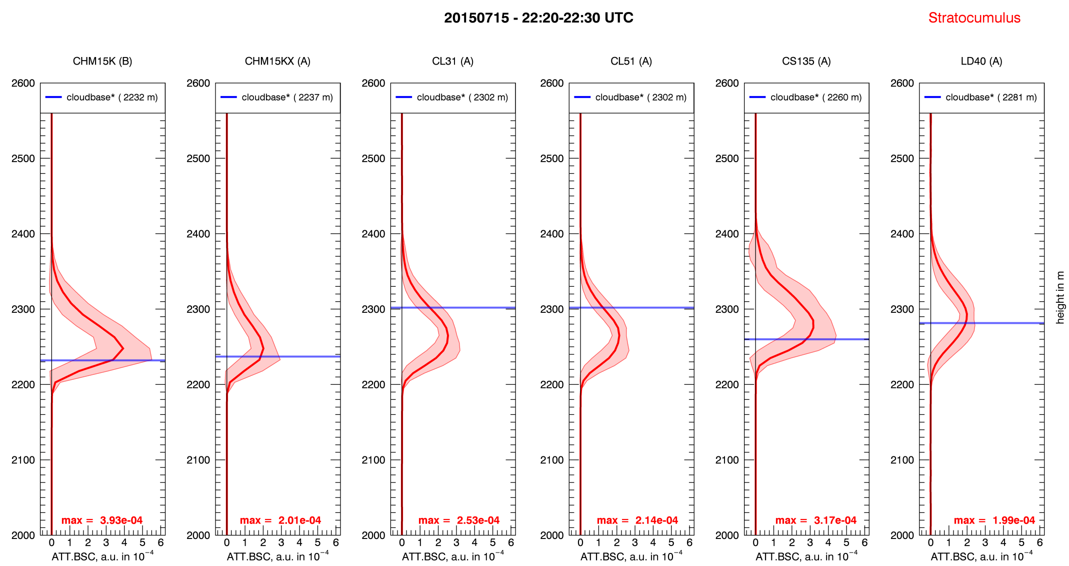

Figure 3. Vertical profiles of attenuated backscatter for the same day as Fig. 2. The profiles are an average over the marked period and they are normalized using an empirical factor.

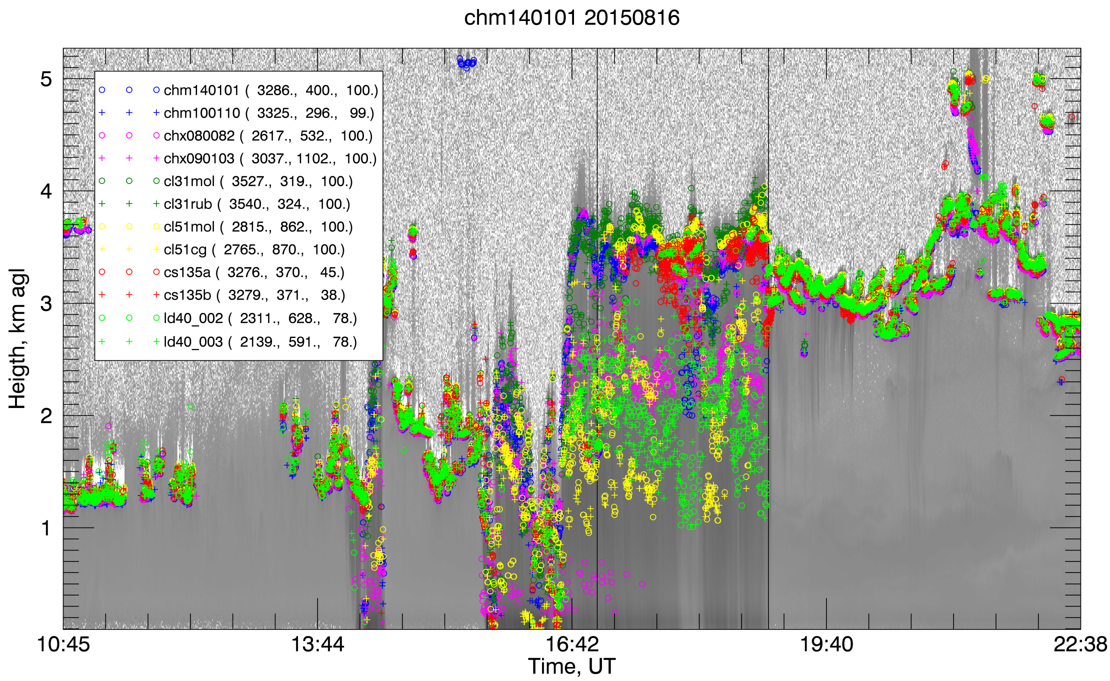

Figure 4. Time-height cross section of $beta_{att}$ (CHM15k-B) and CBH time series of all ceilometers for Cumulunimbus and temporarily heavy rain, the brackets in the inset contain the mean and standard deviation of CBH and the detection rate for a period marked by the vertical lines.

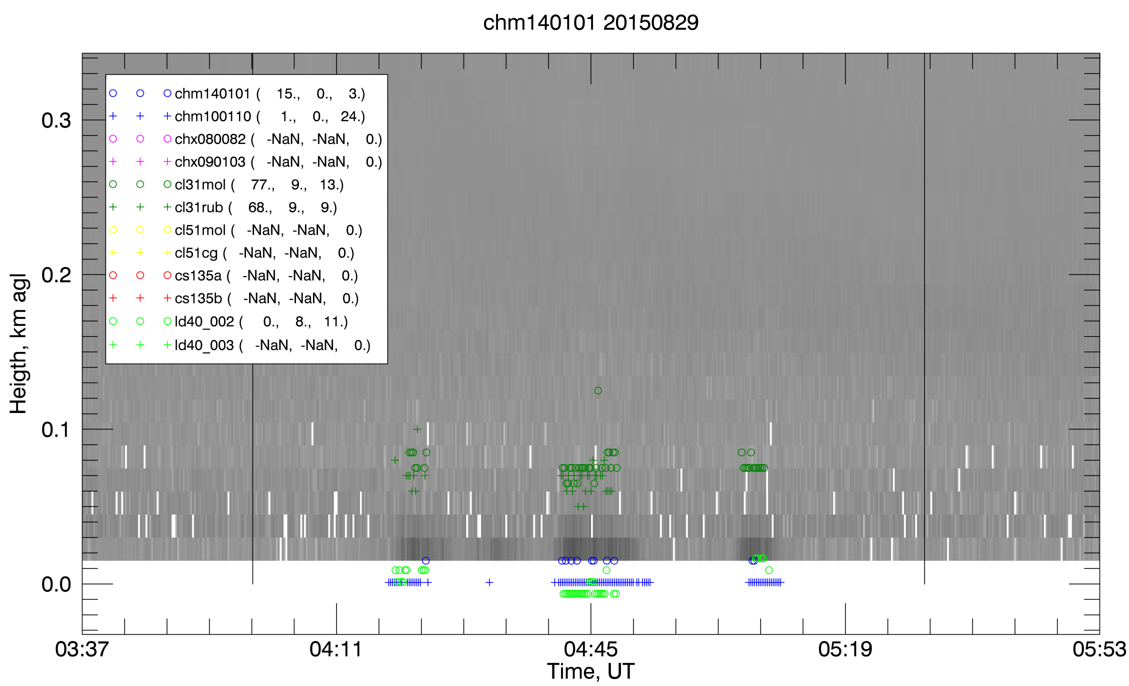

Figure 5. Time-height cross section of $beta_{att}$ (CHM15k-B) and CBH time series of all ceilometers for clear sky, the brackets in the inset contain the mean and standard deviation of CBH and the detection rate for a period marked by the vertical lines.