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Atmospheric Measurement Techniques Discussions

Ceilometer-lidar inter-comparison: backscatter coefficient retrieval and signal-to-noise ratio determination

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Abstract

The potential of a new generation of ceilometer instruments for aerosol monitoring has been studied in the Ceilometer-Lidar Inter- Comparison (CLIC) study. The ceilometer is of type CHM15k from Jenoptik, Germany, which uses a solid state laser at the wavelength of 1064 nm and an avalanche photodiode for photon counting detection. The German Meteorological Service is in progress of setting up a ceilometer network for aerosol monitoring in Germany. The intercomparison study was performed to determine whether the ceilometers are capable to deliver quality assured particle backscatter coefficient profiles. For this, the derived ceilometer profiles were compared to simultaneously measured lidar profiles at the same wavelength. The lidar used for this intercomparison was IfTs multi-wavelengths Raman lidar Polly^{XT}. During the EARLINET lidar intercomparison campaign EARLI 09 in Leipzig, Germany, a new type of the Jenoptik ceilometer, the CHM15k-X, took part. This new ceilometer has a new optical setup resulting in a complete overlap at 150 m. The derived particle backscatter profiles were compared to profiles derived from Polly^{XT}s measurements, too. The elastic daytime particle backscatter profiles as well as the less noisy night-time Raman particle backscatter profiles compare well with the ceilometers profiles in atmospheric structures like aerosol layers or the boundary layer top height. The calibration of the ceilometer profiles by an independent measurement of the aerosol optical depth (AOD) by a sun photometer is necessary to determine the correct magnitude of the particle backscatter coefficient profiles. A comprehensive signal-to-noise ratio study was carried out to characterize the ceilometers signal performance with increasing altitude.

1 Introduction

The German Meteorological Service (DWD) is presently being setting up a ceilometer network. About two-thirds of 60 planned instruments are already in operation. The network uses the new Jenoptik ceilometer of type CHM15k. This ceilometer uses narrow line width laser and an avalanche photodiode for the signal detection in photon counting mode. Due to these specifications these ceilometers have the potential to explore the vertical aerosol distribution. The primary intention of the network was operational synoptic cloud base observations. Besides the cloud base range finding aerosol detection by ceilometers has been studied before, mainly using instruments from Vaisälä (e.g., Sundström, 2000; McKendry et al. , 2009). These ceilometers use a comparatively broad line width laser which complicates the daylight background suppression. Markowicz et al. (2007) found that the Vaisälä CT25K aerosol profiling is mostly limited to the boundary layer, but it is capable of detecting events in the lower atmosphere such as mineral dust events between 1 and 3 km. A study by Martucci et al. (2010) is comparing Vaisälä CL31 and the Jenoptik CHM15k cloud base height detection. In this study they notice that the CHM15k return shows a higher sensitivity to the aerosol detection (i.e., more features are detected below the cloud base).

To study the ability of the Jenoptik ceilometers to quantitatively detect the vertical aerosol profile the retrieval of the particle backscatter coefficient profile from the ceilometer data was investigated. To do so, the comparison to an independent assessment of this profile is indispensable. One of the DWD ceilometers is located at the regional DWD weather center in Leipzig which lies at about 2 km distance from IfT. As will be shown by the compared profiles, the horizontal variability of the aerosol is small enough to allow a representative intercomparison. We used ceilometer data from a period in April and May 2009 when simultaneously measured profiles from one of IfTs multi-wavelengths aerosol lidars, the portable Raman lidar system Polly^{XT}, were available. An example of a daytime measurement of the intercomparison will be shown.

Another opportunity for ceilometer-lidar intercomparison occurred in May 2009 when the European Aerosol lidar network (EARLINET) Reference Lidar Intercomparison campaign 2009 (EARLI 09) took place in Leipzig, Germany. The goal of this campaign was to assure the quality of the lidar measurements of five EARLINET reference stations. In the frame of this intercomparison campaign several commercially available lidars and ceilometers were placed aside the EARLINET lidars to study their ability

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to detect aerosol layers. Among them was a Jenoptik ceilometer of type CHM15k-X. These measurements were used for the intercomparison study as well. The lidar used in the intercomparison was again IfTs lidar Polly^{XT}.

In this contribution, we present the results from the ceilometer lidar intercomparison study including a comprehensive signal-to-noise ratio analysis. The latter allows the characterization of the signals performance of the ceilometer and thus determine how accurate aerosol layers can be detected by the Jenoptik CHM15k(-X) ceilometers. In the following chapter the instruments and their characteristics are presented. Thereafter the data retrieval methods are explained and the main results from the CLIC study are shown and discussed.

2 Instruments

Polly^{XT} is a fully automatic multi-wavelengths Raman lidar using a frequency doubled and triplet Nd:YAG laser (Althausen et al., 2009). It detects the signals at the three elastically backscattered wavelengths, two Raman shifted wavelengths, and one depolarization signal. The detection mode for all channels is photon counting plus one fast analog channel at 532 nm. With this configuration, Polly^{XT} fulfils the requirements of an EARLINET 3 backscatter + 2 extinction + 1 depolarization lidar. Simultaneously to the emitted light at 532 nm and 355 nm wavelengths Polly^{XT} emits pulses at 1064 nm wavelength with 180 mJ at a repetition rate of 20 Hz. This results in a laser power of 3.6 W at 1064 nm. The primary receiving mirror of the Newtonian telescope has a diameter of 300 mm. The vertical resolution of the data acquisition is 30 m and the data are typically stored with a temporal resolution of 30 s.

The Jenoptik CHM15k(-X) is a one-wavelength near-infrared laser ceilometer. Its optical design is based on separated lens telescopes of 100 mm diameter for the transmitter and receiver. A microchip Nd:YAG laser with a central wavelength of 1064.10 nm and a line width of 0.38 nm serves as the light source. The narrow line width and stable wavelength of the solid state laser facilitate an excellent background light suppression

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The pulse energy of the laser is 8 4µJ at 5–7 kHz resulting in a laser power of about 50 mW. The avalanche photo diode (APD) is used in photon counting mode and the signal in detected with a resolution of 15 m . Within the DWD network the data are stored with a temporal resolution of 15 s or 30 s. The instrument type CHM15k is the standard instrument with a complete overlap at about 1500 m and a measurement range of 15 km. A new version of the instrument, the CHM15k-X has a 4-times wider field-of-view and improved optics facilitating a complete overlap at 150 m. Further details on the Jenoptik ceilometers are described by Flentje et al. (2010) and Frey et al. (2010).

In terms of expected signal-to-noise performance of the ceilometer the lower laser power, the smaller receiving optics, and the higher noise of the APD detection compared to that of the lidars photomultiplier must be taken into account. Thus, the signals received by the ceilometer are noisier than those of the lidar and the altitude range up to which aerosol can be detected is limited.

3 Data evaluation

The temporal development of the logarithm of the range corrected ceilometer signal is revealing the aerosol structures in a time-height section (Fig. 1). The ceilometer data were stored every 30 seconds. This results in several thousand data profiles per day and allows to plot the range corrected signal in a proper temporal resolution. Together with the vertical resolution of 15 m quite detailed aerosol structures can be resolved in almost the entire lower troposphere down to a height of at least 150 m above the ground.

To retrieve vertical aerosol profiles the data from the ceilometers and the lidars elastic channel at 1064 nm were analyzed using the Fernald-Klett method (Fernald, 1984; Klett, 1981). By this method the particle backscatter coefficient is derived applying a backward iteration starting at a chosen reference height. The method requires independent information on the lidar ratio and on the reference value of the particle backscatter

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coefficient. During night-time the lidar data can be evaluated by the Raman method (Ansmann et al. , 1990) using also the signal from the Nitrogen Raman channel at the 607 nm. From this measurement the extinction coefficient profile is calculated without any assumptions. The retrieval of the particle backscatter coefficient profile, again, requires a reference value. Due to the wavelength dependence of the molecular scattering process, the scattering efficiency for atmospheric particles at 1064 nm is much lower than that for the other lidar wavelengths. Therefore, the calibration of the raw data profile by a reference value chosen at an altitude where no particles but only the molecules contribute to the measured signal is more difficult in the infrared light spectrum. In the case of the ceilometer measurements the low signal and high noise level (see chapter 5) above 5 km exacerbates this calibration. An example of different reference height choices and the resulting particle backscatter coefficient profile and aerosol optical depth (AOD) value is shown in Fig. 2. In this example the AODs calculated from the profiles using different reference heights differ significantly by a factor of about 2. Therefore, the correct magnitude of the particle backscatter coefficient profile can only be determined by a calibration with an independent measurement of the AOD.

At IfT the AOD is measured by the Aerosol Robotic Network (AERONET) sun photometer in Leipzig. This sun photometer measures the radiance at eight channels ranging from 340 nm to 1640 nm. For the comparison with the lidars and the ceilometers AOD the sun photometer measurement at the 1020 nm channel was used. The AOD from the ceilometer and lidar data are derived by integrating their extinction coefficient profiles. These extinction profiles are calculated from the respective particle backscatter profiles using the assumed lidar ratios that are valid for the respective aerosol layers. For simplification, in this study a constant lidar ratio of 55 sr is assumed that is valid for continental urban aerosol, for Saharan dust (Müller et al. , 2007), and for volcanic ash plumes (Papparlardo et al. , 2010) over Europe for both the lidar and the ceilometer. For the presented intercomparisons one should also keep in mind that the deviations of the real lidar ratio from the assumed one are not relevant since both data sets are treated equally. To calculate the resulting AOD from the extinction profiles, the

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extinction values at the height range with incomplete overlap below 1 km were extrapolated as constant and set equal to the extinction value at 1 km height. This invokes indeed a certain error which can be estimated to about 20% in the cases with high aerosol load presented in this paper up to 50%., in other cases when the BLT is below 2 km.

The vertical smoothing length of all lidar and ceilometer profiles shown is 330 m.

4 Ceilometer lidar inter-comparison

Two representative cases of CLIC (ceilometer-lidar inter-comparison) are shown and discussed in this paper. The first case is a daytime measurement from the DWD Ceilonet that shows that the background stray light leads to much noisier signals and reduces the maximum height for the retrieval of the particle backscatter coefficient profile. The other case is a night-time measurement during EARLI 09 with lower background noise-level which allows to identify the aerosol structures easier than during daytime.

4.1 Daytime case

The example of daytime profiles was measured on 1 May 2009 from 12:00–15:00 UTC (Fig. 2). The plot shows the three hour mean Fernald-Klett derived particle backscatter profile from Polly^{XT} from the 1064 nm channel and the particle backscatter profile derived from the ceilometer measurement. The overall comparison of both profiles shows good agreement in the observed aerosol structures and a noisier profile at higher altitudes in the ceilometer measurements. Both instruments observed the boundary layer top at about 1 km height and a pronounced aerosol layer above the boundary layer reaching up to about 4.5 km. Above this height the noise in the ceilometer signal is increasing with altitude. In contrast, the less noisy lidar profile is still resolving a weak aerosol layer at the height range from 8 to 12 km. The particles observed at those altitudes may origin either from long-range transport of ashes from volcano eruptions earlier that year in Alaska or may be Saharan dust particles as well. FLEXPART calculations (not shown) at these heights indeed indicate a contribution of volcanic ashes from the Alaskan volcano outbreaks during winter and spring 2009. The presence of Saharan dust is less likely since neither the FLEXPART calculations nor the DREAM dust forecasts (www.bsc.es) indicate any dust over Leipzig.

To quantify the differences in the profiles, the AOD was calculated from the derived extinction profiles as described in chapter 3. On 1 May 2009 the AOD derived from the ceilometer profile is 0.18 and the one from the lidar profile was calculated to 0.17. The independent measurement of the AOD by a sun photometer yields a value of 0.15 at 1020 nm. These are differences of about 11% and 12% which may also due to the extrapolation of the extinction profile to the ground with a constant value. Overall, these differences are small and the profiles compare quite well.

4.2 Night-time case

The example of a night-time measurement was taken during EARLI 09 on 25 May 2009 from 21:00–23:00 UTC. During night-time the Raman channels of Polly^{XT} can be used and the particle backscatter profile at 1064 nm was calculated from the ratio of the signals measured at 1064 nm and the ones measured in 607 nm Raman channel. This measurement is shown in green in Fig. 3 and compares very well with Polly^{XT}s elastic backscatter profile at 1064 nm derived using the Fernald-Klett method. The corresponding particle backscatter profile derived from the ceilometer data is shown in red. To verify the correctness of the absolute values of the particle backscatter coefficients of all three profiles the occurrence of a cirrus cloud between 11 and 13 km can be used. The wavelength independence of the clouds backscatter allows an adjustment of the lidar profiles at three wavelengths to an equal reference value inside the cloud of 8 Mm^{-1} sr^{-1} in this case. The reference height was chosen at 12 km. For the retrieved data from Polly^{XT}s signals this adjustment was done for both the particle backscatter profiles from the elastic wavelength and the Raman particle backscatter profile. This additional check acts as a prove for the correctness of the retrieved particle backscatter coefficient values.

Regarding the aerosol structures in the profiles measured by both the ceilometer and the lidar the boundary layer top at almost 2 km height is detected. Another aerosol layer above the boundary layer is reaching up to 6.5 km height. On this day a Saharan dust outbreak was observed over Europe. This was indicated by the corresponding DREAM forecasts (www.bsc.es). The dust layer was present over Leipzig during the whole night and its structure is well resolved by both the lidar and the ceilometer profiles. However, the particle backscatter coefficients of the ceilometer profile are a bit lower, especially between 2 km and 4 km height, which also results in a slightly lower calculated AOD. The AOD calculated from the elastic lidar profile is 0.108 and compares very well to the values of 0.109 calculated from the Raman profile. The AOD calculated from the ceilometer profile is 0.101. These are only small differences that definitely remain inside the measurement errors and the profiles are in good agreement. Note also, that the increase of the noise with altitude in the ceilometer particle backscatter profile appears to be less during night-time compared to the daytime particle backscatter profile. A more detailed analysis of the signal noise follows in the next chapter.

5 Signal-to-noise ratio

For the characterization of the ceilometers ability to detect aerosol layers at the different altitude levels qualitatively, the signal-to-noise ratio (SNR) has to be calculated. The SNR of a lidar or ceilometer signal is defined as the wanted signal divided by the unwanted signal.

The total detected signal P_{tot} consists of the backscattered signal P_{sig} plus the background signal P_{bg}:

$$P_{tot} = P_{sig} + P_{bg} \tag{1}$$

and

$$P_{sig} = P_{tot} - P_{bg} \tag{2}$$

Taking Gauß' error propagation law for the calculation of the signal noise ΔP_{sig} into account, we get:

$$\Delta P_{sig} = \sqrt{\Delta P_{tot}^2 + \Delta P_{bg}^2} \tag{3}$$

Since the detection mode of both the ceilometer and the lidar is photon counting their signal noise follows the Poisson statistics. The error of a counting rate is equal to its quare-root and is essentially shot-noise. Hence, with Eq. (3) it follows:

$$\Delta P_{sig} = \sqrt{P_{tot} + P_{bg}} = \sqrt{P_{sig} + 2P_{bg}} \tag{4}$$

Finally, the SNR can be expressed as:

$$\mathrm{SNR} = \frac{P_{sig}}{\sqrt{P_{sig} + 2P_{bg}}} \tag{5}$$

In the following the SNR of the presented measurements are discussed.

During daytime (Fig. 4) the SNR of the ceilometer signal is higher than 1 up to about 4 km height. At this height, the top of the main aerosol layer is reached. Above the aerosol layers the SNR is decreasing rapidly below 1. For comparison, the SNR for the Polly^{XT} signal is shown. Due to the higher laser and receiver power it decreases below 1 above 12 km height. This means also that – in contrast to the ceilometer – Polly^{XT} is able to measure the weak backscatter signal at 1064 nm from the atmospheric molecules. The ceilometer is only capable to measure the signal backscattered from particles.

During night-time the altitude where the SNR of the ceilometer signal is decreasing below 1 is depending on the aerosol load and is mostly around 5 km. In cases of high

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aerosol load in mid altitudes – as during a Saharan dust event over Europe – the SNR can also be above 1 at higher altitudes. The example of the night-time measurement from EARLI 09 is shown in Fig. 5. Here, the SNR is greater than 1 up to 6.5 km, which is the dust layer top, even for a 30 min mean profile. Above this height the SNR increases again in the cirrus range where the signal gets high again. The signals from Polly^{XT} are above 1 up to the cirrus cloud and stay around 1 even above. Thus, although the first impression from the particle backscatter profiles during night-time (Fig. 3) implied a better SNR at higher altitudes, the SNR calculation shows the limits for the quantitative aerosol data evaluation from the ceilometer signals.

6 Conclusions

From the SNR study we can conclude that the ceilometer is able to detect aerosol layers in the boundary layer and up to about 4 km height during daytime. During night-time when background noise is low aerosol layers can be detected even up to higher altitudes. However, the SNR is depending on the presence of aerosol layers and decreases rapidly if the aerosol content declines. In the case of the Saharan dust event over Europe on 25 May 2009, the dust was observed at high altitudes also with the ceilometer. In this case the SNR was greater than 2 up to 6.5 km when averaging over half an hour. However, although the particle backscatter coefficient profiles from both instruments compare well in aerosol structures, the correct values of the particle backscatter coefficients can only be determined from ceilometer data when integrating the derived profiles to AOD values and compare their values to an independent measurement of the AOD, e.g. from a sun photometer. Here, also the unknown lidar ratio has to be assumed for the respective aerosol type.

A network of ceilometers for the determination of the aerosol distribution over an area like Germany would need at least a few anchor stations with AOD measurements from sun photometers. At these stations also a lidar would be helpful to determine the correct particle backscatter coefficient. With the measurements from these anchor stations also a scaling of all ceilometer profiles of the network would be possible and thus contribute to the spatial aerosol monitoring over Germany or even Europe.

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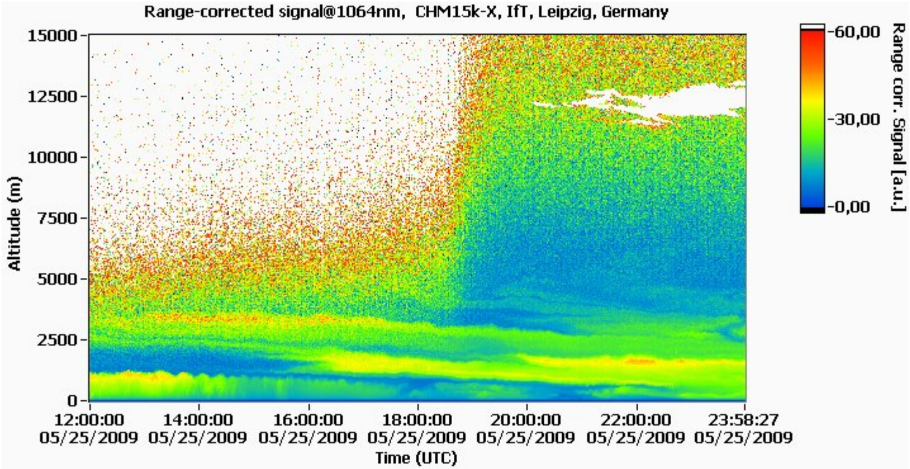

Fig. 1. Temporal development of the range corrected signal of the ceilometer Jenoptik CHM15k-X on 25 May 2009 from 12:00–23:59 UTC. The data have a temporal and vertical resolution of 30 s and 15 m, respectively.

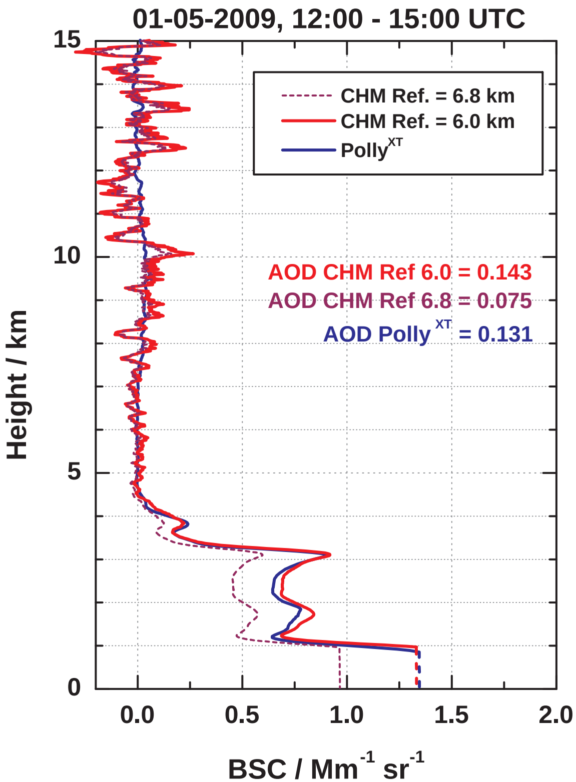

Fig. 2. Daytime particle backscatter coefficient profiles derived from the ceilometer data (in red) and lidar data (in blue). The mean AOD measured by the AERONET sun photometer for this time period is 0.147. Different results for particle backscatter coefficient profiles are obtained by variations of the reference height chosen for the retrieval from the ceilometer data. For instance choosing the reference height at 6.8 km results in the particle backscatter coefficient profile in dashed purple and a calculated AOD of the 0.075 which is too low.

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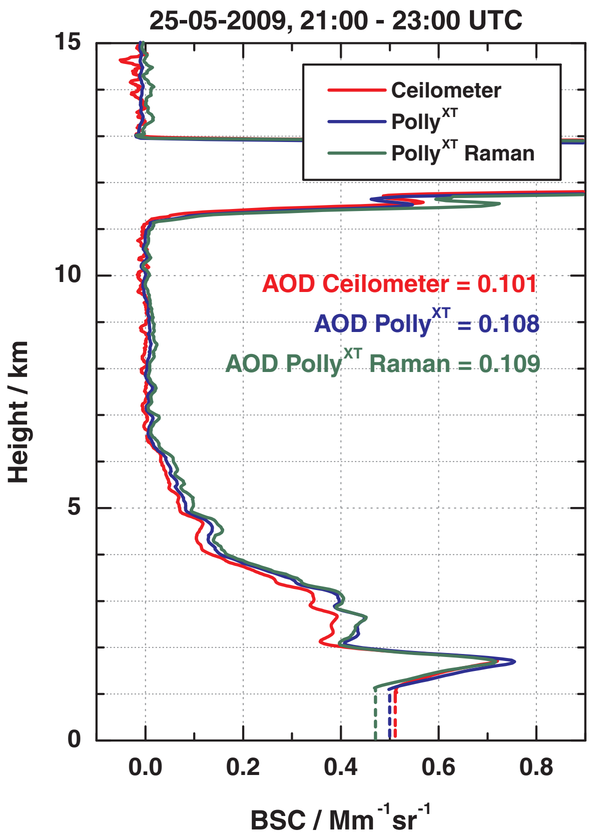

Fig. 3. Particle backscatter coefficient profiles derived from ceilometer data (in red), lidar data (in blue), and Raman lidar data (in green). The AOD measured by the AERONET sun photometer for this time period is 0.119.

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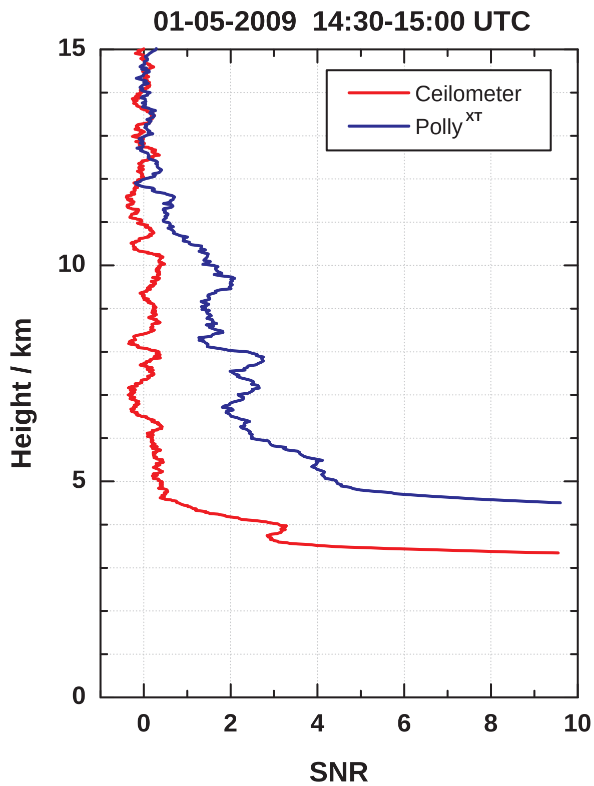

Fig. 4. SNR of a 30 min mean ceilometer and lidar signal on 1 May 2009 during daytime.

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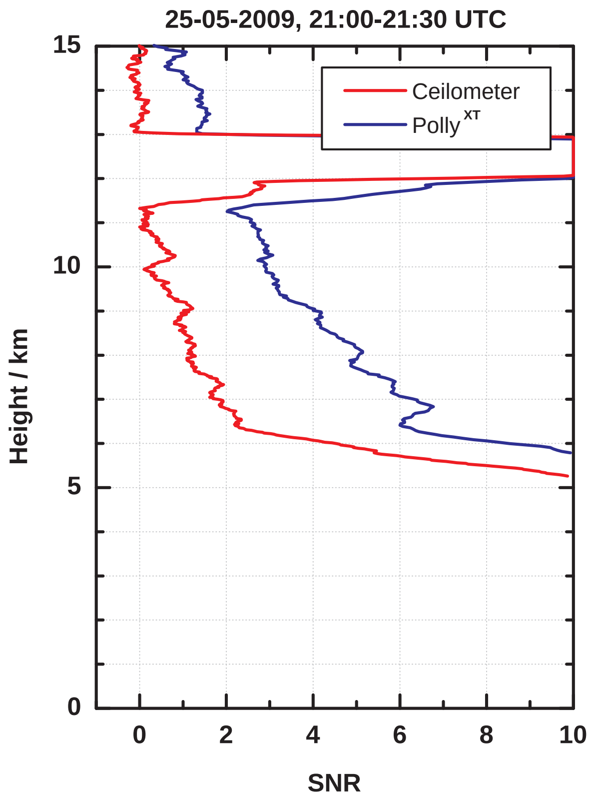

Fig. 5. SNR of a 30 min mean ceilometer and lidar signal on 25 May 2009 during night-time.

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