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Atmospheric Measurement Techniques
Discussions

Interactive comment on "What is the benefit of ceilometers for aerosol remote sensing? An answer from EARLINET" *by* M. Wiegner et al.

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Introduction

We want to thank reviewer #5 for his/her critical review and the suggestions for improvements and clarifications – they were very helpful. We repeat the points raised by the reviewer and add our comments in italics. At the end of our replies we include the revised version of the abstract.

Point by point replies

- The paper would be useful to the science communities and potential users of the ceilometer measurements. The paper provides a detailed discussion on the

retrieval issues such as lidar calibration, selection of lidar ratio, correction for geometrical overlap and water vapor absorption and their impact on the retrieval accuracy. However, the current writing of the paper has not well answered the question about to what extent a ceilometer can provide quantitative measurement of aerosols. The authors summarize in the abstract that "the retrieval of β_p with a relative error in the order of 10% seems feasible", this is a useful conclusion but needs to explain more about in what condition it is feasible (spatial and temporal averaging and at what altitudes).

  → *In fact it would be desirable to provide one number characterizing the accuracy of the retrieved β_p. In the manuscript we pointed out – as the reviewer states – that the error is in the order of 10 % under certain conditions. We have clarified this statement as suggested in Sect. 4.2.1: P2503/l21 now reads: "From an extensive error calculation an overall uncertainty of β_p in the order of 10 % was found for soundings of the boundary layer in Munich, Germany, and a temporal resolution of a few minutes. Thus, data can easily be used for near real time applications." And P2504/L22: "The variability of C_L can be accounted for by periodical re-calibration. This might reveal a larger uncertainty of the applied C_L and hence to a reduced accuracy of the β_p-retrieval."*
  It is now emphasized that it depends on the accuracy of the calibration of the ceilometer how accurate the β_p-retrieval is, i.e., it depends on the stability of the individual ceilometer, the meteorological conditions at the ceilometer-site (e.g., the aerosol distribution, absence of clouds), and the availability of additional data as explained in the manuscript. It is obvious that the accuracy furthermore depends on the signal-to-noise ratio. It depends on the ceilometer type, the background radiation (day/night), the stratification of the aerosols (transmission loss due to low level aerosol layers), and spatio-temporal averaging. As a consequence it might happen that under certain

conditions the uncertainty is (significantly) larger than 10 %. An estimate of this increase is unrealistic: it is the responsibility of the operator of the site to determine the actual accuracy of his/her measurements. We want to stress that at the present state only a (very) low number of case studies is available. The above mentioned investigation concerns a multi-year set of data and thus can be considered as typical for Jenoptik CHM15kx measurements in Munich. It is one of the main purposes of this manuscript to stimulate more investigations to have a broader experience from different ceilometer types and different sites. In Sect. 8 we have listed a few programs that will contribute to this. See also our reply to reviewer #1 with respect to the calibration and the TOPROF cost action.
We have also adapted the abstract accordingly (see below).

- Although, as stated in the paper, only β_p might be derived quantitatively from ceilometer measurements, with the ceilometer β_p measurement, useful information of the vertical distribution of aerosols in the lower troposphere can be extracted. In this context, Figure 13 provides a useful quantitative assessment of the capability of ceilometers to detect aerosol layers, which should be summarized in the abstract.

  → *Following this comment and comments of other reviewers we have rephrased parts of the abstract. The new version is attached to the end of this document.*

- And, it would be useful to quantify the difference of the base (and/or top) heights of elevated layers detected by MUSA and the ceilometer, and provide a similar plot of mean/median base (or top) height difference as a function of altitude.

  → *Figure 13 only aims at providing an example of the reduced sensitivity of ceilometers to detect aerosol layers in different altitudes compared to a li-*

dar. It is used to generally show that the ceilometer's signal to noise ratio, lower than that of an EARLINET type research lidar, is a very good reason for being careful when using ceilometer data for e.g. the establishment of climatologies of elevated aerosol layers. An elaborated quantification of the deviation between ceilometers and lidars in retrieving geometrical properties and a more detailed comparison between the attenuated backscatter and other properties provided by three ceilometers and the collocated MUSA lidar will soon be provided in another manuscript currently in preparation for the this special issue of AMT.

Minor comments:

- While Fernald et al are probably the ones who in their 1972 paper first introduced the two-component form of solution of the lidar equation to the lidar community, Klett is the one who demonstrated in his 1981 paper that a backward inversion of the lidar signal is more stable than a forward inversion. As I noticed, some lidar researchers may refer to a backward solution as "Klett solution". The authors use both terms of "forward" and "backward" Klett solution throughout the paper. I would suggest simply using "forward" or "backward" solution.

  → *We have modified the text as suggested by the reviewer: whenever it read "forward Klett" oder "backward Klett", we have omitted "Klett".*

- Equations (8), (13) and (14): missing term of S_p in these equations.

  → *Thanks a lot for the careful reading. In Eq. (9) S_p was correctly introduced, but indeed forgotten in Eq. (8) and the corresponding equations (13) and (14) ("copy and paste"-error). As it was a typo, the conclusions remain unchanged.*

- Equation (19): more explanation is needed for W_i; how these weights are determined in practice?

  → *To make the whole section clearer, we first of all have added explicitly the information that α_w is the absorption coefficient averaged over the spectrum of the laser (P2510, L4 of the original manuscript). The wavelength grid λ_i as used in Eq. (19) is covering the assumed spectral range of the laser. In our case the central wavelength is assumed to be "somewhere" in the range between 905 nm and 910 nm (see previous comment on P2509, l23, of reviewer #1) and the width of the interval is of the order of 5 nm (typical for most Vaisala ceilometers). In our manuscript we discuss two examples covering the ranges 903–907 nm and 905–910 nm, respectively, to account for the possible variation of the emission. The selection of adequate λ_i is the responsibility of the user of the ceilometer, one can use a line-by-line model or approximations with a reduced but representative number of grid points to reduce the computational costs. We feel that approximative methods are sufficient as usually only the approximate spectrum of the laser is known. In our first example we have divided the whole interval into 50 sub-intervals, each described by up to 4 representative wavelengths; in the second example there are 62 sub-invervals. That means that $w_i = 1$ for those of the 50 (or 62, respectively) sub-intervals where one wavelength is sufficient to represent this sub-interval. In cases where one sub-interval is represented by (say) 4 wavelengths the sum of the 4 weights is 1 (but the 4 weights normally are different). In our example we end up with N=92 in Eq. (19) for the interval from 903–907 nm, and N=133 for the interval from 905–910 nm. So, depending on the model and the selected λ_i the weights w_i are fixed. The procedure is given in detail in a paper submitted to JQSRT in March 2014.*
  We want to emphasize again that the requirement is to determine an effective absorption coefficient of water vapor for the aerosol retrieval from

  ceilometer measurements (Eq. 18). This could be done with a radiative transfer model of choice, but it has to take into account the very large number of absorption lines of water vapor in this spectral range. A similar reply was given to a comment of reviewer #1.
  We have also added the following information (P2511, L3 of the original manuscript): "The absorption data are based on the HITRAN spectroscopic database (Rothman et al., 2005) and the MT-CKD continuum model (Clough et al., 2005)".

As mentioned, and triggered by comments of different reviewers we have also modified the abstract:

→ *With the establishment of ceilometer networks by national weather services a discussion commenced to which extent these simple backscatter lidars can be used for aerosol research. Though primarily designed for the detection of clouds it was shown that at least observations of the vertical structure of the boundary layer might be possible. However, an assessment of the potential of ceilometers for the quantitative retrieval of aerosol properties is still missing. In this paper we discuss different retrieval methods to derive the aerosol backscatter coefficient β_p with special focus on the calibration of the ceilometers. Different options based on forward and backward integration methods are compared with respect to their accuracy and applicability. It is shown, that advanced lidar systems as being operated in the framework of the European Aerosol Research Lidar Network (EARLINET) are excellent tools for the calibration, so that β_p-retrievals based on forward integration can readily be implemented and used for real time applications. Furthermore, we discuss uncertainties introduced by incomplete overlap, the unknown lidar ratio, and water vapor absorption. The latter is relevant for the very large number of ceilometers operating in the spectral range around $\lambda = 905 - 910$ nm. The accuracy of the retrieved β_p mainly depends on the* *accuracy of the calibration and the long-term stability of the ceilometer. Under favorable conditions, a relative error of β_p in the order of 10 % seems feasible. In case of water vapor absorption, corrections assuming a realistic water vapor distribution and laser spectrum are indispensable, otherwise errors in the order of 20 % could occur. From case studies it is shown that ceilometers can be used for the reliable detection of elevated aerosol layers below 5 km, and can contribute to the validation of chemistry transport models, e.g., the height of the boundary layer. However, the exploitation of ceilometer measurements is still in its infancy, so more studies are urgently needed to consolidate the present state of knowledge which is based on a limited number of case studies.*

Interactive comment on Atmos. Meas. Tech. Discuss., 7, 2491, 2014.