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Atmospheric Measurement Techniques
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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 # 1 for his/her careful reading and the provision of a large number of comments and suggestions – it helped us to improve the paper. We repeat the points raised by the reviewer and add our comments in italics. If necessary we also refer to comments given by one of the other reviewers. As several comments of other reviewers lead to modifications of the abstract we have added the new version at the end of this document.

Point by point replies

The analysis focuses on the main ceilometers that can be used for such a purpose. Uncertainties, biases and ranges are given in the text (sensitivities may be also given), but as a lot of information is given, it is not quickly and precisely available to the reader. I would thus recommend that the authors add a few tables to synthesize their findings and summarize the main characteristics of the ceilometers, their advantages/drawbacks, give calibration and inversion uncertainties, biases, and ranges/sensitivities estimates in the specific conditions tested.

→ *We have followed the general suggestions as far as possible, details are given below. However, one should keep in mind that it is not feasible to cover all atmospheric and instrumental conditions that have an influence on the accuracy of the result (e.g. β_p) and the number of publications that can be cited is very low. Consequently the goal of our manuscript is twofold: first, to make operators and users of ceilometer data aware of the different pitfalls of the data evaluation before interpreting optical properties, and second, to stimulate more studies on aerosol retrievals at different sites and using different ceilometer types. The first goal implies that upcoming publications should consider the actual errors (caused by issues discussed in this paper) taking into account the actual measurement situation (instrument, meteorological conditions). Due to the lack of studies it is not possible to give a survey of the β_p-accuracy (asorted by instruments and sites/climate zones), and summarizing errors as tables is difficult per se and could be misleading: we want to avoid references like "According to Wiegner et al. (2014) the error is x %." Nevertheless we have synthesized our findings (and added one table) to facilitate the reading.*
We also want to point out that a detailed discussion of very specific issues must be given in companion papers, in particular with respect to applications. This includes layer detection (methodology, comparison with reference lidar systems) or validation of transport models. It is impossible to cover all of these topics in depth in one paper! As a consequence, more papers are foreseen to be submit-

ted to this AMT special issue (see also reply to comment on P2518, l20-29) or as individual research articles.

Detailed comments

- P2492, l11: define EARLINET

  → *Done*

- P2492, l12: “for calibration”

  → *Replaced as suggested.*

- P2492, l15: add information on the Day/Night range and sensitivities obtained by the analyzed ceilometers in terms of particulate backscatter coefficients (see the comment related to section 7.1)

  → *We have added this information to the abstract; see end of this document.*

- P2492, l18 : remove last sentence "as a consequence...", its place is more in the conclusion.

  → *We agree with the comment and have removed this sentence. The message is indeed part of the conclusions.*

- P2493 , l17 : add references on representative lidar systems for the characterization of optical and microphysical aerosol properties. May be remove or displace this sentence, as this is discussed after in page 2494.

  → *As proposed, we have removed the sentence here and pointed out by using "advanced lidar concepts" that these systems are – due to the physical basis – better suited for aerosol remote sensing than systems based on elastic backscattering. Examples with references are given in the following paragraph; see also our reply to the reviewer’s comment on P2494, l17.*

- P2494, l3 : "shape" may be beyond the capabilities, more likely "non-sphericity"

  → *This is true; we have changed this.*

- P2494, l17: I do not understand why the authors refer here to the EARLINET measurement procedure, which is not defined from aerosols characteristics but from operational constraints. EARLINET stations are not operating continuously, which is one advantage of ceilometers, but they could be operated differently, provided the observations are made on a regular basis.

  → *As a part of the introduction we wanted to make clear that "aerosol remote sensing" aims at a large variety of parameters including geometrical properties (e.g., layer detection, extent), optical properties (extensive and intensive, e.g. α_p or S_p) and microphysical properties (particle size). This was the motivation for the establishment of EARLINET, i.e. the development/improvements of instruments that allow to derive these parameters. From these statements the reader should however not conclude that "all problems are solved". The main reasons are – as the reviewer states – operational constraints (strictly speaking: it’s too expensive). This is mentioned in the manuscript. This dilemma led to the discussion of the potential of ceilometers. This is explained in the following paragraphs.*
  To make the text more clear we extended the first sentence of the paragraph in this way: "By the end of the 1990’s the need to upgrade lidar systems for a better characterization of aerosol particles, and the need of coordinated

measurements to increase the density of information became evident. This was the main driver to establish ..., which is based on Raman lidars with additional spectral and polarimetric channels."
Details of the different steps of upgrades are given in the overview-paper to this AMT-Special Issue.

- P 2495, l3: we see further in the paper that ceilometers can give access to backscattering coefficient and their data be used as inputs to models. The authors should come back on the complementarity between ceilometers and lidar networks in section 7.2 and/or 8.

  → *We have added a sentence in Sect. 7.2 as suggested: see comment on P2520, section 7.2 by this reviewer. Furthermore, we want to point out, that* β_p *from ceilometers are not used as input for models yet. To our knowledge (based on communications with colleagues of national weather services and scientists working on data assimilation) first attempts to assimilate ceilometer data are under investiation but far from being operational. We have therefore change the order of the last words of the paper from "data assimilation" to "assimilation of ceilometer data".*

- P2495, l16 : the definition of ceilometers by wavelength appears to me very specific to the authors. It should be explained first that the ceilometers are designed and built to operationally detect clouds (as mentioned later in p2498, move p2498, l24-26 at the beginning of this section to address this point). This has led to the development and commercialization of a few systems. I do not see why low power micropulse lidar systems operating at other wavelengths could not also be identified as ceilometers. But once again, this is more driven by required performance (allowing low sensitivity), technology and costs.

  → *We agree that there are several options to define a "ceilometer". We choose*

the "wavelength criterion" because such systems are by far most frequent and operated by large organizations (e.g. weather services). As a consequence it is most likely that users want to use rather this data-source than data from small networks or single stations. Thus, we see an urgent need to comment on the actual potential of such widespread systems, that means it should be avoided that such data are interpreted in a way that is not legitimate. It has often happened to one of the authors (MW) that at conferences and meetings it was claimed that ceilometers provide extinction coefficients or mass concentration. We are aware that other systems are on the market (e.g. Leosphere and Raymetrics in Europe), and that other networks are existing (MPLnet is mentioned in the paper). However, many of these systems are customer specific, more complex or can be used in different configurations, so a complete coverage and discussion of all systems is far beyond the scope of this paper. Moreover, such systems are typically intended to measure aerosols and used in a "scientific way", so the risk that the data are misused is much smaller.
A brief motivation for this paper is given at the end of the introduction. We could not go too much into details in the manuscript, but we have added one clarifying sentence: "We choose this definition as such commercially available and widespread systems will most likely be used for purposes that are beyond their original intent."

- P2496, l11 and following : a list of various ceilometers is presented. The characteristics of the main systems often referred to in the study would be worth being reported in a table.

  → *When we prepared the paper we were also thinking about a table as suggested. At that time we dropped this idea because the available information on the different types is quite incomplete or not published, in particular when concerning the data acquisition.*

For this paper the most relevant properties are the wavelength, the overlap characteristics, the pulse energy and the field of view (for the measurement range and SNR). The wavelengths are either 1064 nm (Jenoptik) or 905–910 nm (most Vaisala ceilometers except the LD-40): this information is given in the paper. With respect to the overlap, the systems differ in their optical design: the Jenoptik-ceilometers are bi-axial, whereas the Vaisala-ceilometers are mono-axial. Furthermore, the optical axes (transmitter and detector) of the Jenoptik-systems are slightly tilted (to our knowledge, special tilt angle can be realized if the customer has special requirements). These facts were indeed not explicitly mentioned in the paper, thus, we have added a respective sentence. The pulse repetition rate is in the order of 7 kHz for all ceilometers as mentioned on page 2495, l18 of the original manuscript. The pulse energy is in the range of a few μ*J, with somewhat lower values for the Vaisala-ceilometers.*
With an additional sentence on the optical axes we believe that the relevant parameters are available for the reader; note, that e.g. the wavelengths are mentioned in the paper whenever it is required to understand the text (e.g., for the water vapor absorption). Nevertheless we see the referee's point, that a table would facilitate the reading of the paper. As a consequence we have included the new table Tab. 1 (end of this document).

- P2501, l9 : "technique"

  → *The typo has been corrected.*

- P2503, l26 : measurements are not available at the ceilometer wavelengths identified by the authors, so the presentation of this analysis should be modified to identify what to do in this case.

  → *If radiometer data are used to constrain ceilometer retrievals, a wavelength*

difference must be taken into account in most cases. This was also done in the paper Wiegner and Geiß (2012), where wavelengths at 1020 nm (radiometer) and 1064 nm (ceilometer) were considered. As a consequence a wavelength-dependence of (e.g.) α_p *must be assumed (by means of the Angström exponent* κ*). One can estimate* κ *from the spectral measurements of the radiometer or use typical values for the site and the prevailing meteorological conditions. Note, that many radiometers have a spectral channel close to 1064 nm, so that the procedure described above is not critical. As a reminder of this issue we have added the sentence: "Note, that it might be necessary to account for a wavelength difference between the ceilometer and the photometer."*

- P2504, l10 : define LMU.

  → *The acronym "LMU" is only known from the list of the authors' affiliations, so in fact it can be overlooked. We have changed this sentence to make it clear.*

- P2504, l15 : quantify the error that can be avoided.

  → *It is obvious that comparisons of measurements at different sites are prone to errors due to possible spatial changes of the aerosol distribution. This error source disappears if measurements, strictly co-located, are compared. The quantification of this error can only be provided (for cases studies) if coincident measurements at different sites are made and the horizontal gradient between these sites is determined. As mentioned in our introductory remark publications on the subject of this manuscript are quire rare, in particular we do not know any generally applicable publication dealing with the agreement of vertical backscatter profiles as a function of distance.*

- P2507: at the end of section 4, refer to a table summarizing errors on calibration.

  → *As already argued in the introductory remark we don't think that a table summarizing errors can be provided. We primarily must rely on general considerations (discussion of equations, description of approaches and applicability) and own measurements, because almost no other publications are available yet. As a consequence, the magnitude of "typical" errors can hardly be quantified and summarized in a table. An example might illustrate this: From our (i.e., LMU) measurements (CHM15kx) we could retrieve* C_L *with an accuracy of approximately 5 % (depending on the system-settings) stable over a time frame of three years (see Wiegner and Geiß, 2012). After a recent upgrade the range of the high-voltage settings was increased. This will result in new values of* C_L *for configurations that were not possible before and new long-term characteristics. This has to be assessed. We believe that the value of 5 % is sort of a lower limit, but this statement cannot be verified at the moment. Moreover, corresponding investigations for other ceilometer types are still missing. It can be expected that in one or two years a larger set of data will be available as a calibration-initiative is started in the framework of the TOPROF cost action (see Sect. 8) including a few EARLINET groups. With this experience a table might be set up.*

- P2508, l9: typo F:="

  → *Corrected.*

- P2509, l7 : be more explicit on Raman wavelengths that could be used, and mention that extinction is determined from the transmission obtained at this wavelength and at the emission wavelength, so that in fact an extrapolation is already needed to determine S_p using Raman scattering. It can be thus further used for ceilometer data correction.

  → *The extinction coefficient* α_p *is determined from the signal at the Raman wavelength. Assuming a realistic wavelength dependence,* α_p *at the elastic wavelength is derived. Note, that the wavelength difference is small: in the UV it is 32 nm (387 nm-355 nm), in the visible 75 nm (607 nm-532 nm). Combining the Raman- and the elastic signals provides* β_p *at the elastic wavelength, and finally the lidar ratio at that wavelength. As a conclusion, an assumption on* $\alpha_p(\lambda)$ *for each of the two (small) wavelength intervals is required. This is typically done by assuming an Angström exponent* κ*; in most cases the same* κ *is used for the UV and the visible wavelengths. The resulting wavelength dependence of* S_p *(over the comparably large wavelength interval of 177 nm) can however be different, e.g., if the wavelength dependence of* α_p *and* β_p *is the same,* S_p *is wavelength independent. One can try to use this information to extrapolate* S_p *to 1064 nm, however, the uncertainty is large as the change of* S_p *with wavelength might even change its sign as suggested by model calculations of Saharan dust (Gasteiger et al. 2011b).*

  We conclude that a reliable estimate of S_p *in the infrared is difficult, but of minor importance in view of the low extinction coefficients. We have slightly modified the corresponding sentence to "... and Raman lidars only provide* S_p *at 532 nm and/or 355 nm, and spectral extrapolation could be critical; see e.g. Gasteiger et al., 2011b." Our recommendation how to handle this problem is given in the last sentence of Sect. 5.1 of the manuscript. In this context we want to mention that we have – though not explicitly requested by the reviewer – shortened this paragraph (P 2509, l9-17) as it was sort of lengthy and did not significantly contribute to the focus of the section.*

- P2509, l23, explain why the emission wavelength may vary by as much as 3 nm.

  → *According to Vaisala (personal communication, see acknowledgments of the manuscript) the emitted wavelength is varying a little around the nominal*

905 nm as a function of ambient temperature, because the source is not thermally stabilized and the emitted wavelength is temperature dependent. Moreover, the initial wavelength of individual laser components will vary. The spectral width of the laser is around 3.4 nm FWHM. The reason for this is the temperature rise of the laser chip active area of about 5 K during the pulse length of 110 ns. Vaisala points out that this is noticeably wider than individual absorption lines, and thus reduces the total effect of absorption. We want to emphasize again, that the ceilometers are primarily designed for cloud detection, not for quantitative aerosol profiling.

- P2510, l7 : give a reference for DIAL measurements and constraints.

  → *Publications on DIAL are quite frequent and go back to the 1970's (Scotland, 1974; Browell et al., 1979) or even earlier. The inclusion and discussion of the DIAL methodology for water vapor retrievals would by far exceed the scope of the paper. To be consequent, we then must also include a discussion on the Raman-methodology for water vapor retrievals and its constraints. We want to emphasize, that we have mentioned these techniques only for the sake of completeness; the availability of DIAL measurements is certainly quite rare. As a compromise, we have changed "DIAL" to "differential absorption lidar".*

- P2512, l19-20 : precise/give the domain of variation of the wavelength lambda-i.

  → *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) and the width of the interval is of the order of 5 nm (typical for most Vaisala ceilometers). In the paper we discuss two examples covering the ranges 903–907 nm and 905–910 nm, respectively, to account for the possible variation of the emission. Using a λ_i-grid with a very high spectral resolution in Eq. 19 provides a high accuracy for the effective transmission in any case. In that case, w_i would be the same for all λ_i and can be normalized to 1. However, to reduce the computational costs we use in this paper a wavelength-grid with a reduced number of grid points. Therefore, we divided the spectral interval into sub-intervals, and determined for each sub-interval so-called representative wavelengths λ_i with weights w_i that approximate high spectral resolution results. 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. The procedure is given in detail in a paper submitted recently to JQSRT as mentioned in the paper.
See also our reply to a similar comment of reviewer #5.

- P2512, l26 : at the end of section 5, summarize in a table the possible water vapor interference range.

  → *We want to refer to our previous comments on the inclusion of tables. The same arguments apply here. It should be added that on P2512, l3-5 (original manuscript) we have given concrete numbers of the possible errors (based on idealized examples) and mentioned that the uncertainty depends on the water vapor concentration and the spectral range. By the way we are planning a dedicated publication on the sensitivity of aerosol retrievals in the presence of water vapor absorption; see also comments to reviewer #4.*

- P2513, l15: is there any saturation effect in the measured signal to account for?

→ *To our knowledge there are no saturation effects. It might be possible that in case of dense fog saturation occurs but signals under such situations are useless for aerosol remote sensing anyway.*

- P2514, l20 : in turbulent conditions, the mixed layer is usually developed, and it is also possible to use vertical profiles. However, both in the vertical and horizontal, the profile in the surface and mixed layers may have a gradient and be spatially inhomogeneous. May be discuss more this point, as no optimal solution exist, but operation may be easier in a case than in the other.

  → *To find a homogeneous range of the atmosphere is (unfortunately) difficult, as spatial gradients can occur all the time. The probability to find adequate conditions is much higher if horizontal measurements are performed. This is the experience of years of vertical lidar measurements of our own and of colleagues inside and outside of EARLINET. Note, that in case of horizontal measurements you can demonstrate that the atmosphere is homogeneous in the range just beyond the full overlap. Thus, it is very likely that this is also true for a closer range. In case of vertical measurements you never can be sure! Of course, horizontal operation is not the standard procedure and extra effort is required, but it is feasible for many systems.*
  See also our reply to a comment of reviewer #2 on P2514, L12.

- P2515, l21: "not on"

  → *Corrected.*

- P2516, l17 and after: mention that profiles are taken during nighttime.

  → *We have added this clarification in two sentences.*

- P2517, l11: discuss more quantitatively the "slightly better performance" in terms of signal-to-noise-ratio (SNR).

  → *The main message of this paragraph only should be that the measurement range of state of the art ceilometers allows to detect even high clouds. We have demonstrated this by Fig. 11 and visual inspection and the (in fact) qualitative statement of the "slightly better performance". As an explanation for our findings we now have added: "This is plausible in view of the different pulse energies of the ceilometers (see Tab. 1) and potentially larger transmission at 1064 nm". A more detailed discussion would imply the fundamentals of the determination of cloud heights. If this topic should be discussed in this paper, it should be inserted in Sect. 7.1.*
  As a consequence of the feasibility of cloud detection, manufacturers provide automated schemes that deliver a certain number (often 3) of cloud bottom heights and/or the vertical extension of the clouds. These algorithms are (as far as they are made public) based on the ratio $P(z)/\sigma(z)$, with σ being the standard deviation of the signal at the far end of the range (e.g., from 14 km to 15 km). If required, this ratio can also be calculated by the user and be treated as a proxy for the SNR. σ can be height depended if different smoothing procedures and/or time averaging are involved. A cloud is detected if empirical thresholds (typically proportional to the above mentioned ratio) are exceeded. The exact information on the algorithms are however kept secret. This situation is similar to the case of aerosol layer detection and mixing layer height assessment as mentioned in the paper. Thus, we added the following sentence at the end of Sect. 7.1 (as a side note because this Sect. primarily deals with aerosols): "It should be briefly mentioned, that for cloud detection automated schemes are provided, typically based on the ratio of the signal and the standard deviation of the signal at the far end, and the exceedance of empirical thresholds."

With respect to Fig. 11 and our statement of a "slightly better performance" we want to clarify that this results from "single profiles" (in fact, these are averages over 30 s and 36 s for the CHM15kx and the CL51, respectively) in the best spatial resolution (i.e, no smoothing took place, with range bins of 15m and 10 m for the CHM15kx and the CL51, respectively). From visual inspection the statement is obvious – see comment above. One option to obtain a quantitative assessment is the consideration of the above mentioned ratio $P(z)/\sigma(z)$ on the basis of single profiles. It confirms the conclusions from the visual inspection: e.g., between 6 km and 7 km and between 20:00 UTC and 22:00 UTC the ratio is between 1 and 3 in case of the CHM15kx, whereas it is between 0.3 and 0.6 for the CL51. These numbers should be treated as approximate values as the variability with height and time is extremely large in cirrus clouds. Note, that temporal averaging and smoothing would increase the potential of cloud detection (larger SNR).

- P2518, l8: acronym STRAT not defined.

  → *STRAT means "Structure of the Atmosphere". We have added this information to the manuscript.*

- P2518, l20-29: it would be preferable for the continuity of the text and discussions to move this part into the previous section 6 dedicated to the measurement range. A new subsection 6.3 may then be created for this purpose. Also, give the sensitivities in terms of backscattering coefficients corresponding to MUSA measurements, for the CHM15k at the identified maximal ranges (3 and 5 km).

  → *There are indeed several options to organize the paper. From our point of view we wanted to have a dedicated section concerning "popular" applications, i.e., the most demanded products from the community. We feel that at the present stage this is the detection and attribution of layers (clouds and*

aerosols) and the validation of transport models. Next steps will probably be the link of ceilometer networks to advanced lidar networks, and data assimilation as briefly pointed out (see our reply to comment on P 2495, l3, of this reviewer). As no other reviewer requested a shift of this part and as reviewer #1 did not express a strong requirement, we would like to leave the section as it is.

With respect to the second part of the comment we agree that the sensitivity of layer detection as a function of height, properties of the layer (e.g. extent and optical depth), and transmission of the atmosphere below the aerosol layer is an interesting topic. A full elaboration would however go far beyond the scope of this paper. That is the reason why a companion paper dealing with comparisons between ceilometer measurements and EARLINET lidar measurements is in preparation and will be submitted to this AMT special issue.

- P2520, l20: optical depth or mass concentration cannot be determined but they can be estimated using a priori parameters and relationships or using AERONET data. Mention it and give a reference.

  → *Thank you for this comment. This is exactly one of the reasons for writing this paper. We want to show that only β_p can be determined, with an error probably not below 10% and highly depending on the accuracy of the calibration constant. As the reviewer states, optical depth or extinction coefficients cannot be derived unless one makes additional assumptions (including additional errors). The derivation of mass concentration requires even more additional assumptions, e.g. mass to extinction conversion factors. This procedure requires as a first step an estimate of the extinction coefficient (assumption of S_p is required) and in a second step the conversion factor that depends on the microphysics of the particle ensemble (see e.g. Gasteiger et al., 2011a). As a conclusion if mass concentration (e.g. of a*

volcanic ash layer) is provided, the contribution of the ceilometer data to this output is limited (vertical extent of the layer, and β_p if certain requirements are fulfilled), all other contributions are provided by other instruments, by model calculations and assumptions. That does not mean that ceilometer data are useless, but one should be aware of the contributions!
To make this clear we have added the following sentences to Sect. 8 (note, that the first paragraph has also been changed according to a comment of reviewer #4 on Pg 2521, ln 7): 'We want to underline that the derivation of "advanced" products as e.g. the mass concentration of a volcanic ash layer requires information from additional instruments and/or model calculations. Thus, statements like "mass concentration was derived by ceilometer measurements" should be avoided. Ceilometers only provide the spatial extent of the layer and – under certain conditions – β_p*, all other information (e.g. extinction coefficients, mass-to-extinction conversion factors) are based on different sources (see, e.g., Gasteiger et al., 2011a, Perrone et al., 2012). Consequently, the accuracy of the retrieved mass concentration primarily depends on the accuracy of parameters that are not derived from the ceilometer.'*
We feel that this statement best fits to Sect. 8, because in Sect. 7.2 we want to rectrict ourselves to the usefulness of ceilometers alone. In Sect. 7.2 we have introduced a sentence as it was proposed in the next but one comment of the reviewer.

- P2520, l21: "operationally provided"

  → *We have added this.*

- P2520, section 7.2: add one or two sentences on the combination of lidar and ceilometer networks as inputs for the validation and exploitation of CTMs.

  → *We have added more information as requested by including the following sentences: Emeis et al. (2011) demonstrate in their Figure 14 how the DWD ceilometer network has successfully been used for the validation of the simulated arrival times of the first ash cloud (16./17. April 2010) over different parts of Germany. Furthermore, the calculated altitude and the vertical extent of the layer could be confirmed, taken into account the reduced resolution of the model.*

- P2522, l10: examples are given but other actions exist, verb is missing. Possibly start the sentence as "One can mention EUMETNET's...".

  → *We have rephrased the sentence as suggested.*

- P2532, Fig. 3: plot results with respect to relative difference or ratio as in Fig. 6.

  → *We have now plotted the ratio instead of the difference as the reviewer suggested. As a consequence the text was adapted, in particular it is mentioned that the large relative error around 5 km corresponds to a small absolute error as* β_p *is very small (shown in Fig. 1). Furthermore we have streamlined the text and restricted ourselves to the most relevant conclusions, see also replies on the 5. and 12. comment of reviewer #2. The new paragraph reads: "… Plotted is the ratio of the retrieved and the true (i.e. the model input)* β_p *for clear and turbid conditions, and when the lidar ratio is underestimated (*$S_p = 40$ *sr) or overestimated (*$S_p = 60$ *sr) by 10 sr. Solid lines refer to the forward approach, dashed lines to the backward approach. In case of the forward approach two lines each are plotted according to the different overlap heights* z_{ovl}*. It can be seen that the magnitude of the uncertainty introduced by wrong* S_p*-estimates is of the same order of magnitude for the forward and backward approach, but the height dependence is different. In the lowermost part of the troposphere it is below 2 % and 5 % for the clear* *and turbid case, respectively. Larger uncertainties in the order of 10 % only occur in case of the forward approach around 5 km, however, the absolute errors remain small due to the rapid decrease of β_p (see Fig. 1). The influence of the z_{ovl} on the forward approach is comparable small and can be neglected for any practical applications."*

- P2534, Fig5 : in legend "...different water vapor..."

  → *Corrected.*

- P2535, Fig6 : in legend "...retrieved and true ... different water vapor..."

  → *Corrected.*

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.

Table 1. Overview over key parameters of selected ceilometers: “prf” is pulse repetition rate and “rfov” the receiver field of view (half angle). Data are from user manuals of Vaisala and Jenoptik, respectively. The Jenoptik CHM15k is now known as “Nimbus”. Note, that the axes of the CHM15kx are tilted by 0.46 mrad.

	Vaisala			Jenoptik	
	CT25k	CL31	C51	CHM15k	CHM15kx
wavelength [nm]	905–910			1064	
optical concept	mono-axial (single lens)			bi-axial	
prf [kHz]	5.6	10	6.5	5–7	5–7
pulse energy [μJ]	1.6	1.2	3	8	8
rfov [mrad]	0.66	0.83	0.56	0.23	0.85

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