Response to reviewer 1's comments for Operational performance of the Vaisala CL61 ceilometer for atmospheric profiling

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We would like to thank the reviewer for the constructive comments. Below are the reviewer comments in black text, followed by our responses in blue text. Where applicable, we also provide changes to the manuscript in *blue italics*.

- Lines 14–15: I find the current formulation confusing, as it combines two distinct effects (the particle-versus-volume effect and the background bias correction). I suggest describing these effects separately. Based on my understanding (and Fig. 10), the molecular contribution accounts for nearly all of the reported effect, whereas the residual background bias is essentially negligible. This should be stated explicitly, as the fact that the firmware almost completely removes the mean background bias is, in my opinion, an important outcome of the study

Thank you for the valuable feedback, we modified it as following:

In a case study representing low aerosol load conditions in Finland, correcting for the instrumental bias changes the volume linear depolarization ratio by up to 0.005 relative to the instrument-provided values. On the other hand, the difference between volume linear depolarization ratio and particle linear depolarization ratio reached up to 0.1. These findings demonstrate that the CL61 firmware effectively removes the majority of the mean background bias, whereas accounting for the molecular contribution is important for quantitative interpretations of aerosol measurements at CL61's wavelength of 910.55 nm

- Line 68: The overlap correction function remains constant, whereas the actual overlap function may vary. Please add the term "correction" for clarity

Thank you for the valuable feedback, we modified it as following:

The overlap function is reported only in the new firmware (version 1.2.7), and no overlap function has been reported for the instrument at Lindenberg. Although the overlap function might change during operation, for example due to temperature variations (Hervo et al., 2016), the overlap correction applied to the data reported by the CL61 remains constant.

- Line 119: For future reference (e.g. if this issue is resolved in subsequent firmware releases), it may be useful to specify the firmware version(s) in which the issue is present

The firmware versions were mentioned in Table 2. We added more clarification to Line 74 to highlight this:

The firmware versions of the instruments (i.e. 1.1.10 and 1.2.7), along with their respective periods of validity, are presented in Table 2.

- Line 219: Replace "50 μm" with "50 m"

Corrected

- Line 341: In practical applications, is a depolarisation ratio of 0.001 meaningfully different from ratios of 0.002 or 0.005 (line 397)? Some discussion of the practical significance of these differences would be helpful

The difference in the depolarization ratio is small in absolute terms; however, the changes in the profile shape are noticeable (see Fig. S6). After removing the instrumental bias, the profile becomes smoother, with the abrupt change in values around 150 m no longer present. This effect is expected to be most pronounced under clean atmospheric conditions, where the aerosol profile remains consistently low. Although the absolute change introduced by the correction is small, it effectively reduces the depolarization ratio by approximately half in this case.

Overall, the impact of the bias correction is expected to be most pronounced under clean atmospheric conditions, such as in this case in Finland, where the δ profile remains consistently low. The correction improves the overall shape of the profile, particularly around 150 m, by removing the artificial peak in $xpol$ at that height (Fig. S6). However, the change remains small in absolute terms.

- Equation (23): I believe the term should be σ^2 rather than σ

Corrected

- Figure 10: The coloured band should also be described in the figure caption, rather than only in the main text

Thank you for the valuable feedback, we modified it as following:

Example of uncorrected and corrected profiles in Kenttärova measured at 2024-06-04 13:01 UTC. a) β' (instrument provided), β'_v (bias corrected and calibrated), β_p, b) $\sigma^2_{\beta'_v}$, $\sigma^2_{\beta_p}$, c) δ (instrument provided), δ_v (bias corrected and calibrated), δ_p, d) $\sigma^2_{\delta_v}$, $\sigma^2_{\delta_p}$. Error bars represent one standard deviation (σ) of the measurements.

- Line 438: Please correct the typo "and and"

Corrected

- Lines 450–451: This effect appears to be related to the molecular contribution rather than to the background discussed immediately above

Thank you for the valuable feedback, we modified it as following:

The magnitude of the residual background bias for all instruments is generally small. In a case study in Kenttärova, the magnitude of the residual bias was approximately 1-2% of the molecular backscatter.

Suggestion: The manuscript could benefit from a summary table ranking the importance of each effect investigated in the study. Such a table would help highlight the main findings. For example:

- Average residual background bias: negligible, the firmware effectively removes the mean bias (the authors could also quantify the residual bias relative to the molecular signal)

- Background noise (variance): important; in particular, early laser ageing can significantly reduce an instrument's ability to detect weak aerosol signals

- Molecular contribution to volume depolarisation: important, especially under conditions of ...

- Calibration drifts: important, particularly when the laser power decreases below 40

- Window fogging: important, ...

Thank you for the valuable feedback, we decided to restructure the conclusions section:

In this study, we investigate several characteristics of CL61 ALC measurements across multiple sites over a three-year period, using methodologies adapted from existing approaches.

First, we examine the temporal evolution of the background noise and its relationship with laser power. The background noise generally increases as the laser power decreases, which is particularly important because laser aging can substantially reduce the CL61's capability to detect weak aerosol signals. For most instruments, internal scaling of the calibration factor effectively compensates for changes in laser power. However, for the instrument at the Lindenberg site with an older firmware version (1.1.10), this compensation becomes insufficient when laser power drops below 40%*, resulting in a drift in the calibration factor. Therefore, regular cloud calibration is necessary to ensure quantitatively reliable profiles, especially when the laser power falls below* 40%*. Additionally, some deviations in the calibration factor were linked to the fogging of the inside surface of the window.*

Second, we performed termination hood measurements to characterize the instrumental residual background bias and noise profiles. The magnitude of the residual background bias for all instruments is generally small. In a case study in Kenttärova, the magnitude of the residual bias was approximately 1-2% of the molecular backscatter. Nevertheless, the termination hood measurements remain crucial, as they allow the instrumental background to be quantified and subsequently used to estimate the uncertainties of the particle backscatter coefficient (β_p*) and the particle linear depolarization ratio (*δ_p*), as presented in this study.*

Third, we found that the instrumental residual background bias and noise profiles are sensitive to temperature and exhibit differences between parallel and perpendicular polarizations. We also recommend discarding the first $50\ \mathrm{m}$ *of measurements, where periodic variations were frequently observed. Instrumental background profiles were obtained across a range of internal temperatures and were subsequently used to correct the bias and estimate its associated uncertainty. These profiles remained stable for at least one month for a given internal temperature, although small deviations appeared over a six-month period. Consequently, we recommend making termination hood measurements at least once across the operating temperature range to characterize the instrumental background.*

Fourth, we demonstrate that the molecular contribution to the measured depolarization ratio can be substantial, reaching approximately 0.1, whereas the impact of residual background bias is only around 0.005 in the same case study. This highlights the importance of accounting for the molecular contribution in CL61 depolarization ratio measurement under low aerosol load conditions.

Finally, we identify window fogging as an important issue affecting CL61 data quality. Fogging of the inside surface of the window was observed in some instruments and resulted in degraded measurements. Identifying and excluding such periods is therefore essential for ensuring the integrity of the dataset and the reliability of subsequent analyses.

Finally, I would be interested to know the physical principles underlying the firmware's determination of the window condition and the scaling of the internal calibration factor. For example, is the calibration compensation based solely on the measured laser power, or are additional variables involved? Since this information is not essential, please do not consider an answer to this point to be mandatory.

We do not have definitive information about this, as the software operates as a black box. The explanation provided in the paper represents our hypothesis.

References

Hervo, M., Poltera, Y., and Haefele, A.: An empirical method to correct for temperature-dependent variations in the overlap function of CHM15k ceilometers, Atmospheric Measurement Techniques, 9, 2947–2959, https://doi.org/10.5194/amt-9-2947-2016, 2016.