

**Measuring cloud optical depth with a balloon-borne microlidar
operated from the stratosphere
AMT egusphere-2025-5095**

We first want to thank the referees for their fruitful comments. Comments from the two referees are copied below using bold fonts. Our comments are written in black (normal font). All the comments of the referees are answered. Differences between the submitted and the revised manuscripts are shown in an attached file generated using the latexdiff package.

Referee1

The article describes the technical and data processing aspects of the balloon-borne lidar BeCOOL. A technique for deriving optical depth of upper tropospheric clouds is also shown. Overall the article is well written, the technique is well described and mature, the overlap calibration is reasonable, the transmission retrieval using forward and backwards integration is correct, the overlap correction and intentional misalignment is novel, the signal normalization using ECMWF is reasonable, and the two approaches for constrained vs. unconstrained optical depth retrievals make sense. I have no major comments or concerns for the article.

Minor points and comments:

The following points can be addressed or ignored by the authors as they choose. They are only suggestions, minor corrections or comments.

1) The Introduction could use a short paragraph about the importance of measuring clouds in the UTLS. Not critical, but it would provide some motivation for flying lidars on balloons.

It is certainly useful to expand the introduction and add such a paragraph. This is in line with the request of the second referee. We have added a short review of other balloonborne lidar (DiDonfrancesco, 2006; Kaifler, 2020) and developed the scientific goals of BeCOOL, focusing on cirrus observation in the TTL and their role in the climate system, also referring to further analysis we made (Lesigne, 2024, 2025).

2) Line 49: "BECool" --> "BeCOOL"

We now only use BeCOOL in the text.

3) Figure 1. Please ensure all acronyms are explained in the caption.

Acronyms used in the figure are now explained in the caption (OBC, Onboard computer, APB, avalanche photodiode). MC2 has been removed.

4) Figure 2. We have started to 3D print our entire detector assemblies using carbon fibre. It is lighter, very rigid, and has nearly no thermal expansion. We have shown the technique to Gordien Strato and Jacques Porteneuve. It might be worth considering for future versions of BeCOOL

This 3D technology was indeed used to develop the microlidar optical head in the frame of the Arctic survey project IAOOS using drifting buoys. The BeCOOL laser head took benefit from these previous developments, but 3D print has not been used for BeCOOL. We will certainly consider the proposal for future versions of BeCOOL.

5) Line 129. Are you referring to the Junge Layer?

Following the review by Kremser et al., 2015, we prefer to refer to stratospheric aerosol layer, in line with the founding paper of Junge and Manson, 1961. We now quote this review paper. We prefer to avoid the term of Junge layer as it is not commonly used anymore in the stratospheric science community.

6) Adding a short paragraph to the conclusions addressing the significance of improved optical depth measurements would tie the article together nicely. Match with the points raised in Introduction paragraph.

We have emphasized how BeCOOL performances made it possible to address some scientific issues: distribution of thin clouds in the TTL (Lesigne, 2024), lifetime of cirrus clouds (Lesigne, 2025), generation of multilayered cirrus by atmospheric waves (in preparation). This request is also in line with a comment made by the second referee.

Referee 2

General comments

The paper describes the design of the Balloonborne Cloud Observing micrOLidar (BeCOOL) and introduces the applied signal processing and cloud property retrieval schemes. The microlidar can be flown on pressurized stratospheric balloons for several weeks. Impressive results from the first applications of the system during the STRATEOLE-2 campaign in 2021-2022 have already been published in an ACP highlight paper by Lesigne et al. (2024) and in Lesigne et al. (2025). With the present paper, the authors provide instrumental and methodological background that helps readers to better understand the data and assess their quality. Therefore, the paper is suitable for publication in AMT.

I recommend providing more scientific background and discussing aspects of the applied methodology in greater detail, as outlined below.

We agree with this recommendation, in line with comments of the first referee. Following these recommendations, the introduction has been modified. This also clarifies what kind of measurements can be expected with BeCOOL microlidar.

Specific comments

1) The introduction should provide more scientific context. Research objectives, technical requirements, and atmospheric parameters to be measured with the new instrument should be discussed, considering also the state of the art and the anticipated advancements.

This comment is in line with the comments of the other referee asking for more scientific background. We have emphasized the technical requirements and made it clearer which are the target atmospheric parameters aimed at (cloud geometrical properties, cloud optical thickness).

2) In Sect. 2, information on the daytime/nighttime performance and operation should be given (in the caption of Fig. 6, it is mentioned that the instrument is not operated during daytime, but this is not discussed anywhere).

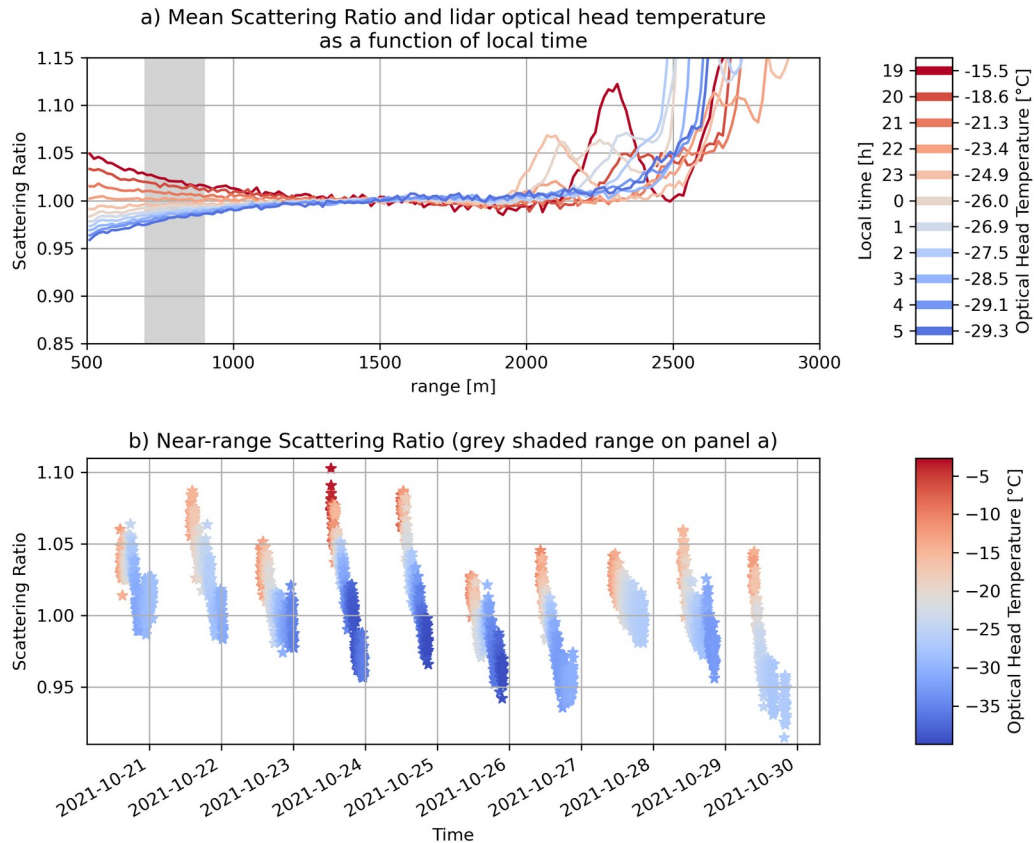
To avoid any confusion, we made it clear in the introduction and in the figure caption that BeCOOL can only provide nighttime measurement. Some balloon-borne tests have shown that the daytime signal-to-noise ratio is too low, making the retrieval of the raw data impossible. Development is under way to make it possible to operate BeCOOL during daytime (narrower filter, wavelength switch). This is mentioned in the last section as a perspective.

3) The overlap function O and the lidar constant K are treated independently of each other in sections 3.2 and 3.3, respectively. However, as can be seen from Fig. 3 and 4, the normalization range used to determine K is exactly the range where the overlap function has its strongest sensitivity to misalignments (1-2 km distance from the platform). Please explain the combined effect of, e.g., temperature variations, on the retrieval of O and K .

In order to compute the attenuated backscatter profile, we ideally need to determine the overlap function $O(r)$ as a function of range r (section 3.2) and the instrumental constant K (section 3.3). We agree that, on principle, both $O(r)$ and K depend on temperature. $O(r)$ is mostly a function of temperature through the change of the misalignment angle. This is indeed presented in Figure 3a, showing the strongest variation within the first two kilometers below the lidar platform.

K is also a function of temperature as it is strongly and negatively correlated to the temperature of the diode (power and spectral emission), and to a smaller extent on the spectral properties of the reception filter, as can be seen as a whole, in the results

shown in Fig 5. We use the 1-2 km range below the lidar to estimate the value of K , where the atmospheric conditions are the closest to clear sky. As noted by the referee, it is therefore tricky to disentangle the estimates of K and $O(r)$. However, we have checked that the effect of temperature on $O(r)$ is much reduced after the normalization is done to derive the K value. Using the signal in the 1 to 2-km range to estimate K (ie normalizing the scattering ratio to 1) , we have checked that the change in transmission due to the alignment angle dependence on temperature remains smaller than $\pm 10\%$ during all the measurements sequences of a balloon flight, as illustrated on the figure below.



Panel a) shows, as functions of local time, the mean scattering ratio profile and the lidar optical head temperature. The residual error due to temperature-induced changes in $O(r)$ clearly appears between 500 and 1000 m, the uppermost clouds appear at a range larger than 2000 m. Panel b) shows the variation of the retrieved scattering ratio at a distance of 0.8 km below the lidar platform (grey shaded range on panel a) for ten flight sequence of flight ST2_C1_02_STR1 already used for reporting observed K changes in Fig. 5. According to the simulated overlap functions, the residual error at near-range (i.e. the variation of the scattering ratio shown here) is an upper bound for the residual error at any range.

From our simple alignment model, it turns out that the best estimate of the misalignment angle is close to minus 165 μrad , with a variation smaller than $\pm 15 \mu\text{rad}$. This is the reason why we assumed that the overlap function could be considered as constant over time (line 121). We show in Fig. 4 that the region where K is estimated

correspond to the region (1-2 km below the lidar) where the sensitivity to misalignment allows a compromise between alignment error induced in the cloud region and residual error due to the contribution of residual aerosol scattering (both smaller than $\pm 10\%$) in the cloud free region (highest clouds are observed ~ 2 km below the lidar). An error in K would however not significantly affect the estimate of the cloud optical thickness, which is our main goal. This conclusion would not hold to estimate the optical depth of the stratospheric aerosol layer in the first kilometers below the lidar, an issue which is currently investigated. Section 3.2 and 3.3 have been changed to make these points clear. Figure 3a has been updated to show clearly the best estimate of the misalignment angle and its uncertainty.

4) The terminology used in the context of the lidar signal normalization is confusing. For K , the terms “normalization constant” and “instrumental constant” are used. In Fig. 5, a “normalization coefficient” is shown without any further explanation. Please revise the wording and apply consistent terminology.

We should indeed avoid any confusion when we normalize the lidar signal, using Rayleigh scattering as a reference for clear sky observation. We now only use the term instrumental constant when we refer to the value of K .

5) When comparing BeCOOL and CALIOP observations of cirrus clouds, it is necessary to consider the pointing of the instruments. It is mentioned that BeCOOL is nadir-pointing. However, CALIOP pointed 3° off nadir most of the time to reduce the influence of specular reflections from horizontally oriented ice (HOI; e.g., Avery et al., 2020). The pointing is important for the determination of the apparent lidar ratio, because the strong backscatter from HOI drastically reduces the lidar ratio. This effect can contribute to the observed shift in the lidar ratio distributions from BeCOOL and CALIOP, i.e., multiple scattering might not be the only reason. Please discuss how the effect can be (or has been) minimized in your case and provide proper references.

There is unfortunately no reliable data to estimate the possible tilt of BeCOOL. The gondola hosting the lidar is certainly gently swinging. On average, we assume that BeCOOL is looking to the nadir, but this is only true on average. Regarding HOI, the reviewer is right, we will mention it and refer to CALIOP in the manuscript (Avery et al., 2020). HOI may partly account for the shift in the lidar ratio distribution from CALIOP and BeCOOL. But we do not see any way to estimate HOI when retrieving BeCOOL data. Regarding cloud optical thickness, this raises the question of a possible bias at short timescale (estimated gondola swinging period of 10 seconds). Actually, looking to the 2D plots, we did not see any sudden increase in the measured backscattering, which is not a surprise given the 1-minute integration time of the data. Comparing CALIOP and BeCOOL distributions of cirrus (Lesigne 2024) we did not either see any significant bias from a statistical point of view. This is why we think the retrieval we apply is robust,

even if we do not apply sophisticated (ie like the one used for CALIOP) retrieval procedures to BeCOOL data. Regarding the estimate of the uncertainty of cloud optical depth, we only compute the uncertainty due to the noise in the vicinity of a cloud. This estimate is therefore a lower limit as other sources of uncertainty remain (choice of the lidar ratio and of the multiple scattering coefficient). These points are emphasized in the conclusion.

6) More explanation and discussion of the multiple-scattering effect and its correction is needed. The theoretical background is a bit hidden in sections 4 and 5. For non-experts, it might be difficult to follow the in-line equations and to put them into the context of Sect. 3 (equations on pages 5 and 6). It would be better to provide a complete set of variables, equations, and relationships at the beginning of the paper. Alternatively, at least the sought physical quantities should be clearly derived and indicated in sections 4 and 5. Numbering the equations will help with the referencing.

Regarding multiple scattering (we should rather speak of forward scattering due to diffraction here as we are looking to very low optical depth ice clouds), we have provided more references regarding the CALIOP data retrievals, and to what extent it is relevant for BeCOOL (Platt, 1973, Nicolas et al. 1997, Garnier et al. 2012, 2015). We have followed the suggestion of numbering the equations to ease the reading and the referencing within the manuscript. The variable are now named according to AMT guidelines. The theoretical framework we are using is standard. Our main goal is to make it clear how we compute cloud optical thickness and which uncertainty is taken into account. Actually, going back and checking the manuscript and our calculation we have noticed that the relation from the paper of Platt was wrongly written and that we were overestimating the uncertainty of the cloud optical thickness due to the signal noise in the vicinity of a cloud. It turns out that for constrained retrieval, the relative uncertainty is always smaller than 5%. For unconstrained retrieval, it is smaller than 10% (95 % of the time) for optical thickness between 3×10^{-3} and 3×10^{-2} , and smaller than 50% (95% of the time) for optical thickness between 3×10^{-4} and 3×10^{-4} . Of course, those are lower limits of the uncertainty as we do not include the uncertainty on the lidar ratio and on multiple scattering.

7) Discussion in Sect. 4.1 implies that CALIOP measures “true” lidar ratios, but this is not the case. The multiple-scattering effect must be considered in CALIOP retrievals as well, and its influence is expected to be even larger for the spaceborne lidar. In general, η is not constant. It strongly depends on ice crystal size and is thus also a function of temperature and humidity. Consequences for the retrieval of lidar ratios and cirrus optical depth have been discussed in the literature (e.g., Garnier et al., 2015). Please provide more information and references on how multiple scattering is considered in the CALIOP retrievals, which assumptions are made, and how this influences the BeCOOL results that multiple are based on comparisons with CALIOP data.

Regarding BeCOOL data, our aim is only to correct the estimate of the lidar ratio from multiple (forward) scattering. As mention before (comment 5), our estimate of multiple scattering is very simple and purely statistical. For sure, there is an uncertainty attached to this estimate but we see no simple way to address this issue. As mentioned by the reviewer, CALIOP multiple scattering factor has been rather accurately determined on a statistical basis using infrared measurements simultaneously performed by the Infrared Imaging Radiometer onboard CALIPSO (Garnier et al., 2012, 2015). In this paper we take advantage of quasi-simultaneous measurements by CALIOP and BeCOOL, to compare multiple scattering corrected optical depths and adjust the multiple scattering factor in the BeCOOL analysis to match CALIOP results on a statistical basis.

8) The section on data availability is missing. Please provide information on the accessibility of both the balloonborne and the CALIOP data. For CALIOP, include information on data/algorithm version and provide respective references.

A paragraph has been added to provide the information required. We confirm that BeCOOL data are already accessible.

Technical corrections

We agree with all the technical corrections listed below. Requires changes have been done for the revised version of the manuscript. References have been added when mentioning the use of CALIOP data.

Please make sure to explain all abbreviations. Check the use of BeCOOL vs BECOOL.

Fig. 1: In the right panel, inscribe the optical elements that are shown. Explain abbreviations in the figure caption.

Fig. 3: Please hint to the black line (overlap function) in the figure caption.

Fig. 7: The caption mentions “red brackets”. What does it mean? Are these the error bars on the red dots? Please clarify.

Table 1: Use the terms pulse length and pulse energy (not impulsion or impulse). Explain the abbreviations.

Equations: Variables should be indicated with a single letter. Abbreviation-like naming (RCS, BG) should be avoided. The equations should be numbered. Please refer to the AMT submission guidelines.

Line 17: ...constraints...

Line 55: ...spectrally narrow... (not thin)

Line 106: ...two... (not tow)

Line 111/112: Please check the formulation of the sentence starting with “Actually, the raw signal...”.

Line 191, CALIOP lidar ratio database: Please provide reference and access information.

References

Avery, M. A., Ryan, R. A., Getzewich, B. J., Vaughan, M. A., Winker, D. M., Hu, Y., Garnier, A., Pelon, J., and Verhappen, C. A.: CALIOP V4 cloud thermodynamic phase assignment and the impact of near-nadir viewing angles, *Atmos. Meas. Tech.*, 13, 4539–4563, <https://doi.org/10.5194/amt-13-4539-2020>, 2020.

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Nicolas F., L. R. Bissonnette, P. H. Flamant, Lidar effective multiple scattering coefficients in cirrus clouds, *App. Opt.*, 36, 15, pp. 3458-3468, 1997.