Replies to comments by Referee 1

Comments, replies, *„changes in the manuscript"*

The manuscript describes a method to derive the backscatter coefficient of stratospheric aerosol from a novel frequency scanning lidar system. It is of great interest for the scientific community to resolve with high vertical and temporal resolution even low amounts of stratospheric aerosol. They compared their results to passive satellite observations and found a reasonable agreement considering the uncertainties of the spaceborne instruments. The manuscript is well written and structured and fits into the scope of AMT. I would recommend publication after minor revisions.

We appreciate the careful review of our manuscript and the many constructive suggestions you provided. Together with the co-authors, we have carefully considered all of your comments and revised the manuscript accordingly by incorporating the proposed changes and additional clarifications wherever appropriate. We hope that these revisions have improved the quality and clarity of the manuscript.

Main comments:

You derive independently profiles of the Mie and Rayleigh signal similar to the HSRL method. The pure molecular signal would allow you to derive the extinction coefficient from your observations additionally to the backscatter coefficient. It would be a great achievement to deliver the extinction coefficient as well, because (1) you could better compare it to the extinction coefficient derived from the passive satellite observations without the assumption of a lidar ratio and (2) you could derive the lidar ratio of the stratospheric aerosol from FSL. Have you tried to derive the extinction coefficient? If possible, you could add it (as a "cherry on the cake") to the paper, if not, you could discuss why it is not possible to get the extinction coefficient.

Thank you for this valuable comment. Although the spectral information provided by the FSL technique has the potential to enable extinction retrievals analogous to HSRL approaches, the current implementation is limited to the retrieval of aerosol backscatter coefficients. The retrieval of atmospheric transmission required for an independent extinction retrieval has not yet been implemented. Consequently, extinction coefficients can currently only be estimated by assuming a lidar ratio, analogous to conventional elastic backscatter lidar retrievals. Since such an approach relies on an a priori assumption rather than the spectral information provided by the FSL technique, it would not provide additional information beyond the current retrieval. The implementation of an independent extinction retrieval is therefore planned as a future extension of the FSL retrieval.

The following text was added to the publication (chapter 2.2.2): "*The current implementation of the FSL retrieval is limited to aerosol backscatter coefficients. Although extinction could be estimated by assuming a lidar ratio, as in conventional elastic backscatter lidar retrievals, an* *independent extinction retrieval analogous to HSRL is not yet implemented and is planned for a future extension of the method."*

It is good that you prove the consistency of your backscatter coefficients with independent observations by OMPS and SAGE-III. I would consider a comparison to ATLID as well. You state, that the wavelength conversion from 355 to 770 nm hampered the comparison. However, the comparison to OMPS and SAGE also required a number of additional steps and assumptions. If you once have to assume a particle size distribution (PSD), you could easily calculate the backscatter Angstrom exponent from 355 to 770 nm for sulfate aerosol and use ATLID for comparison. Wavelength dependent signal attenuation in the stratosphere is, e.g., discussed in Kar et al., AMT 2026. There is no direct overpass of EarthCARE for your 4 selected comparison cases, but for the September 2024 case, the orbits 1503D or 1510B might be considered.

Apart from the reason mentioned in the paper, we had originally omitted it because it was only suitable for a single measurement, and under background conditions above around 20 km, it is often not possible to derive a meaningful profile. But you are right, a comparison with a spaceborne lidar is of course also interesting and does not require a more complicated conversion than for the other satellite instruments. Using a SAGE PSD, we have now calculated a profile of the expected 770/355 nm ratio of backscattering cross sections. The averaged backscatter coefficient at 770 nm from ATLID measurements within a 350 km radius around Kühlungsborn, derived from the orbit 1510B, is now included in Fig. 4. Sections 2.3 and 3.2 and the appendix have been supplemented with information on the methodology.

Minor comments:

In the introduction the usage of ground-based and spaceborne lidar systems for stratospheric aerosol observations is underrepresented. There are plenty of studies using these lidar systems for the study of stratospheric aerosol. There are studies focusing on volcanic eruptions or wildfire smoke injections as well as long-term monitoring of stratospheric aerosol conditions. The FSL method provides another great opportunity to study stratospheric aerosol additional to the already existing ones.

Thanks for this suggestion. Along with the comments from Reviewer 2, we have added a paragraph regarding spaceborne lidars to the Introduction, and also referenced studies on wildfire smoke injections and the long-term monitoring of stratospheric aerosol conditions.

You use the spectral scanning capability of your laser to derive the spectrum in the receiver. This technique is needed for retrieving the wind speed. There are other (simpler) approaches which use scanning capabilities in the receiver to separate the Rayleigh and Mie signal for the purpose of aerosol retrievals. Please include a short discussion in Sect. 2.1.

We did add a clarification in the first sentence of the abstract, highlighting the universal nature of the instrument. Since the instrument is designed for simultaneous measurements of wind, temperature and aerosols doing Doppler-Mie, Doppler-Rayleigh and Doppler-resonance measurements, a simpler approach could be used for pure measurements of aerosols, but would be insufficient for wind, temperature and resonance measurements. We have added a short discussion to Sec 2.1.

Two short questions about your system: What is the height of full overlap? And is it operated continuously or manually?

The height of the overlap is 20 km. The measurements used for this paper were carried out in manual mode. Since 2025, it has been possible to operate the VAHCOLI system in continuous mode.

Could you indicate the time of sunset and sunrise in Fig. 3 to underline the good performance during daytime?

Done. The vertical solid orange lines denote sunset (16:05 UT, 7 February 2023) and sunrise (06:47 UT, 8 February 2023), respectively.

Technical corrections

L102 The ATLID aerosol retrieval is described in Donovan et al., AMT 2024.

The reference has been added.

Fig 2 caption "APD1 on 28 February"

Done.

L228 ATLID is not a Doppler lidar, but a HSRL

The error has been corrected.

L423 "These …" please provide a noun from the previous sentence to which "these" corresponds to be unambiguous here.

Done.

Replies to comments by Referee 2

Comments, replies, *„changes in the manuscript"*

The paper describes the use of a Frequency Scanning Lidar as an aerosol lidar for stratospheric aerosol observations. It is appropriate for AMT. To my opinion, the full FSL method needs to be better explained. A lot of details are missing. Major revisions are needed.

Thank you very much for the considerable time and effort you invested in critically evaluating the FSL methodology presented in this manuscript. Your thorough assessment helped us to further improve the manuscript. We have carefully addressed all of your comments and hope that our responses and the resulting revisions have further strengthened the focus and clarity of the methodology presented in this paper.

Abstract: Please mention the measurement wavelength!

Thank you for the comment. The abstract has been revised, and supplementary information has been incorporated to improve understanding.

Introduction

P1, l15: stratospheric aerosol may play an important role, but not a central role.

Changed.

P2, l38: I do not believe that space-borne spectrometers are the work horses for stratospheric aerosol observations. Please add to the list: spaceborne lidars, CALIPSO/CALIOP; EarthCARE/ATLID, Aeolus/Aladin together with relevant aerosol-related references. And even China has meanwhile a 532 nm HSRL lidar in space: ACDL/DQ-1, Dai et al., AMT 2024. And recently the launched the second 532 nm HSRL.

The paragraph has been revised to emphasise the importance of spaceborne lidars and to include the four instruments mentioned.

P2, l47: lidar measurements from ground?, from space?, airborne? What do you mean here?

This paragraph refers to ground-based lidars and has been modified accordingly. The suggested references to long-term measurements and observations of wildfire smoke plumes have been added to this paragraph.

P2, l58: Please mention the papers of Trickl et al. (several papers in ACP, long term observation over decades), Sakai et al. (JGR, 2025, long term observations over decades), and maybe Ohneiser et al. (ACP, 2022, Australian smoke), Baars et al. (ACP, 2019, Canadian smoke), Hu et al. (ACP, JGR, Lille lidar, France).

The suggested references have been added to the previous paragraph. The statement has been toned down to indicate that lidars do not always, but often, encounter problems above the Junge layer.

P2, l61-64: The motivation for the FSL lidar sounds not very convincing. One can use a simple 1064 nm backscatter lidar for stratospheric observations. The Rayleigh backscatter is even lower at that wavelength than at 770 nm. Most useful aerosol lidars are multiwavelength systems with laser wavelengths from 355 to 1064 nm. One needs to better stress that this powerful lidar can be used day and night, most lidar cannot provide useful stratospheric information at daytime. And in this context it is necessary to provide arguments why daytime observations or better continuous observations throughout the day are necessary. Otherwise the question remains, why do we need this FSL method?

Thank you for this valuable comment. We agree that the motivation behind the FSL method required further explanation. Accordingly, the paper has been revised to better contextualize the FSL technique within the overall objectives of the VAHCOLI measurement system. In particular, we further emphasize that the FSL approach employs narrowband frequency scanning to spectrally separate Rayleigh and Mie scattering. Unlike conventional elastic-backscatter lidar systems based on Nd:YAG lasers, this enables the simultaneous retrieval of aerosol backscatter and wind, thereby providing additional geophysical information. Furthermore, the motivation for daylight-capable operation has been expanded. Continuous day-and-night measurements are essential for the global deployment of a mobile lidar system, especially at high latitudes, where summer conditions are characterized by very short or entirely absent periods of darkness. The ability to operate under full daylight conditions is therefore a key requirement of the VAHCOLI system rather than merely an additional technical feature.

Methodology

P3, l72: Better use Fernald 1984, not Klett 1985?

Done.

P3, l75: Rayleigh scattering as a function of temperature and pressure is considered in all lidar applications! There is no neglection of the temperature dependence!

The paragraph was ambiguous and has therefore been adapted as follows: *“The Rayleigh reference is then extended downwards, and deviations are attributed to aerosol backscatter. However, this approach is sensitive to uncertainties in the assumed molecular backscatter profile due to* *atmospheric temperature and density variations. Despite this limitation, it remains widely used due to its simplicity and low hardware requirements."*

P3, l78 to P4, l104: Please be short here, EARLINET uses Raman lidars since 25 years, HSRL lidars are used as aerosol lidars also for more than 20 years. There is no need to repeat all lidar basics in such detail. But the essential point is that the lidars have to have two signal channels for aerosol and for molecular signal detection, and then the goal is to provide not only backscatter coefficients, but also, extinction and lidar ratio profiles, and this preferably at several wavelengths. A 'simple' 770 nm FSL backscatter lidar is not just state-of-the-art from this point of view. So, it is necessary to sharpen the motivation for such an FSL. What is the main and unique advantage to run a 770 nm FSL, where is the gap in the global lidar landscape for such a system?

Thank you for the helpful suggestion. The entire paper (including the abstract) has been revised accordingly to clearly highlight the distinctive features of the system and the FSL method employed.

P4, l106: Why do we need an aerosol lidar that samples multiple frequencies within a short time period by changing the laser frequency from pulse to pulse? What is the motivation for such an approach? That should be made very clear here.

We have revised Section 2.1 to provide a clearer description and ensure better understanding. We have also adjusted the wording in other sections where necessary to make the descriptions easier to understand.

P4, l124: What about the receiver unit? Some information about the receiver telescope (primary mirror diameter, etc.) is missing.

The information has been included in a table in the appendix.

P5, l125-129: It remains unclear why we need laser wavelength tuning when we simply want to measure aerosol backscatter profiles at 770 nm?

We have revised Chapter 2.1 and added, amongst other things, the following sentence: *"This method was originally developed at IAP for Doppler resonance measurements at 770~nm to determine potassium density and neutral temperatures with high precision in the mesopause region"*

P5, Figure 1: The sketch is confusing! Why do we see the aerosol peaks in the profiles (to the right…) when using the Rayleigh channel (APD 2)? There is a lot of cross talk?

P5, l135: We need more and precise information how you separate Mie and Rayleigh components when there is so much cross talk! And the question remains: why do we need a

frequency scanning lidar to measure aerosol profiles? Maybe I missed the point and it is explained somewhere. But many readers may have the same problems!

Figure 1 was not clearly understandable and we have revised it accordingly. The right most panel of this figure has been removed, since it was confusing to the reader. These were just the signal strength of the channels, when summing up all frequency bins. To illustrate the cross talk of the channels, we added another figure (Fig. 2) with the Rayleigh and Mie contributions in the two APDs. We have added information to Section 2.2 in order to clarify, that spectra are measured and these spectra are processed to get to the aerosol profiles.

P6, l147: Please provide a reference for Eq. (1)!

A reference to Fernald 1984 has been added.

P6, l163: You need two APDs, not one? You have APD1 and APD2, not a single APD!

We have clarified the statement, stressing that the signal processing is using the complete spectrum of APD1 and by comparing the wings and the peak of the spectrum one can calculate the BSR using only one APD. The second APD is only required due to the high blocking of Rayleigh signal on the first APD for higher altitudes.

P6, l155-162: Is this method similar to Aeolus ALADIN and ATLID methods to separate Mie and Rayleigh signals? Could be mentioned!

Thank you, for your suggestion, we thought about it. While Aeolus ALADIN is similar to a FSL lidar in the fact, that it provides spectrally resolved measurements of Mie-scattering, the general approach is vastly different. The HSRL method of ATLID has even less in common with the FSL method, except for the usage of a Fabry-Perot etalon as a filter. We thus chose to not discuss these methods in detail, to not confuse the reader.

P7, Figure 2: The figure is confusing! The full spectrum of the APD1 is stored and analyzed? This was not mentioned before, or did I miss that? There are three profile the total APD2 backscatter, the APD2 Rayleigh component, and even the APD1 Rayleigh component. How did you compute all this? These are essential points of the aerosol FSL approach and must described in the manuscript.

Yes, indeed the raw data, which the analysis is done on is the full spectrum of APD1 and APD2. Despite it being mentioned in the end of section 2.2.1, we have added text and a figure to ensure this is not missed by the reader since it is so essential. The profiles of the total backscatter and the Rayleigh component are computed on the basis of the measured spectra. We improved the text to further clarify this.

P7, l176: P2,total is scaled to P1,Ray at 15 km! What does that exactly mean?

We have altered the sentence a bit, to make clear, that this is just the regular normalization of two signals to each other, which is common in lidar processing.

P7, l179 and 181: Now two correction factors come into play! Were these essential parameters introduced and mentioned before, when explaining the sketch (Figure 1)? Did I miss this? If they were not introduced, all this has to be improved in such a technical paper. Providing references to other publications is not acceptable.

The correction factors are introduced here in more detail. No connection should be made to Fig. 1. The change in Fig. 1 and the addition of the new Fig. 2 should make this more clear. Additional explanation how the correction factors are calculated and where they originate from have been added to the text.

P9, l225: A comparison with CALIOP observations could be done in the case of the volcanic Raikoke aerosol in the summer and autumn of 2019.

Unfortunately, there are no measurements from the VAHCOLI system prior to 2022, so no observations of aerosols affected by the 2019 Raikoke eruption are to be expected.

P10, 268: The size distribution is unkown and thus the uncertainty in the lidar ratio is high. Why not use the FSL to derive extinction and lidar ratio information? What is the reason not to offer this option?

Please refer to our detailed response to Reviewer 1 (p. 1), where this point is discussed in more detail.

P11, 275-280: All this does not work after the Raikoe eruption in June 2019. The Raikoke plumes were visible in the stratosphere between 14-26 km for the next two years.

This is correct. An impact on stratospheric aerosol levels is to be expected in the two years following the Raikoke eruption. To determine a background lidar ratio, measurements taken between June 2019 and June 2021 have therefore been excluded.

P12, Figure 3: Please add proper tick marks to x-axis and y-axis. What are the reasons for the peaks in the profiles? Hunga-Tonga sulfate aerosol layers? Please clarify! Why not showing the full day observations (from 8:10 UTC on 7 Feb to 8:10 UTC on 8 Feb)? Observations from 15:30 to 8:10 UTC are mostly nighttime observations! But the advantage of the 770 nm FSL are daytime observations! If there were clouds before 15:30 UTC on 7 Feb, one should select another day.

Figure 4 (formerly 3) has been graphically adjusted, both in terms of layout and measurement duration. The measurement duration is now 21 hours. This allows for a better illustration of the different measurement conditions at night, as well as during the day. The figure shows dynamically driven short-term variations in the stratospheric background aerosol layer that are not linked to any specific volcanic eruption.

At the end the question remains: what is the goal of the manuscript? The FSL delivers aerosol backscatter and layering structures of stratospheric aerosol at 770 nm wavelength. No depolarization information is available. Depolarization information helps to distinguish stratospheric wildfire smoke and volcanic sulfate aerosol. The depolarization option is meanwhile a basic requirement for a state-of-the-art aerosol lidar. Such critical points should be discussed as well, maybe in the conclusion section.

Thank you for the comment. This point is correct and important, and it requires an addition to the publication. The measurement configuration in the present paper includes a separate depolarisation channel; however, at the time of the measurement presented here, it was unfortunately not yet operational. As part of the ongoing improvement of the VAHCOLI system, this channel is also intended to be used for measurements in order to obtain additional information regarding whether the observed aerosol is spherical or non-spherical. Based on this, further geophysical interpretations will then be possible.

Text supplemented by (end of chapter 2.1): "*The current VAHCOLI system configuration includes a dedicated depolarization channel. Since this channel was not yet operational during the measurements presented in this study, depolarization data are not included in the present analysis. Future measurements will use this channel to provide additional information on aerosol particle shape.*"