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Atmospheric Measurement Techniques Discussions

Interactive comment on "Aerosol monitoring in Siberia using an 808 nm automatic compact lidar" *by* Gerard Ancellet et al.

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Answer to Anonymous Referee 1

The authors gratefully acknowledge the critical review of the manuscript and the remarks have been carefully taken into account in the corrected version. We hope the new version now emphasizes that the added value is not only related to the analysis of aerosol source identification and seasonal variability in Siberia but also related to the proposed methodology to analyze a 808 nm backscatter lidar. The modifications are shown in red within the new version of the manuscript (see supplementary document)

Major Issues:

The described measurement technique is not introducing any innovative aspect. Since Klett

(1981) and Fernald (1984) papers, tens of research articles were published about elastic lidar signal inversion, together with their pros and cons. For example, the technique described in Section 2 is operational (with some minor differences) since 1999 in the NASA MPLNET lidar network. However, all those different inversion methods using either the retrieved sunphotometer AOD to constrain LR or taking it directly from a model as FLEXPART (or a combination of both), still assume that the LR is constant over the atmospheric column. This might introduce large bias and uncertainties, especially when co-exist different aerosol layers at different altitudes.

We agree with the reviewer that Raman and HSRL lidar do provide better extinction vertical profile retrieval when multiple layers with different aerosol type are present. The purpose of this paper is to assess if an automatic backscatter lidar is still valuable in a remote place such as Siberia, with the additional difficulty that it is running in the IR at 808 nm to reduce cost and meet the eye-safe requirement. Therefore the novelty of the paper is threefold (1) propose a methodology for the retrieval of aerosol optical depth (AOD) based on a CALIBRATED IR lidar in addition to well known techniques based on the use of sun-photometer (section 2.3) (2) assess the retrieved AOD by comparison with AERONET AOD and discuss the variability of the corresponding lidar ratio (section 4.1, 4.2 and 5) (3) analyze daily measurements over two years (18 months of effective measurements) to obtain a statistically significant data set of backscatter vertical profile and total AOD in order to discuss the aerosol sources and variability (section 4.3 and 6).

Regarding the question of multiple layers with different lidar ratio, it is indeed the main drawback when using a backscatter lidar. It is now better recognized in the introduction. However we believe that our results show that the bias in the AOD retrieval remains limited for our database. First the time variation of the vertical aerosol vertical structure (Fig. 7) shows that the main contribution to the basckscatter ratio is within the planetary boundary layer (PBL) reducing the bias due to the assumption of a lidar ratio constant with altitude. Second the comparisons of the lidar AOD with the sunphotometer AOD in section 5.1 show a good agreement (Fig. 9) even though some profiles show multiple layers in Fig. 10 to 12.

We have clarified these different points:

- in the introduction, it is stated that Raman lidar will always be better suited for the aerosol extinction profile retrieval, but that backscatter lidar has been used in the past for aerosol characterization and must be characterized for measurements of AOD and backscatter ratio in Siberia (p.2 l.13-l.24 and p.3 l.20-l.24),
- the originality of the lidar data processing is better explained (new figure 4, new section 2.3 p.8 to p.10, better explanation of the rationale for lidar calibration in section 2) showing that the approach goes beyond the simple use of Klett inversion technique (nighttime direct retrieval, lidar ratio retrieval from a lookup table)
- the section 4 now includes only results of nighttime direct retrieval of the AOD (section 4.1) and discussion of the integrated lidar ratio retrieval which can be used to build the lidar ratio lookup table to be used with the FLEXPART analysis (section 4.2).
- the section 5 now includes a discussion of the AOD retrieval error by a comparison with the daily sunphotometer AOD for the 3 selected case studies, i.e. the main aerosol sources observed in Tomsk: biomass burning, dust, anthropogenic sources (new Fig. 9, more profiles in Fig. 10 to 12, discussion of lidar AOD p.17 to 19)
- the section 5 now includes a discussion of the lidar ratio S_{808} variability when the air mass transport changes for the 3 case studies (discussion of S_{808} p.17 to 20).

For those reasons, the manuscript is unbalanced as a large part of it is dedicated to describe the retrieval technique (including Appendix A and B)

We believe that the paper is not balanced towards the description of the measurement technique as a large part of the paper is devoted to the analysis of the variability of aerosol sources and to the comparison with sun-photometer and satellite data for three "typical" aerosol sources encountered during the analysis (14 pages for the discussion of the results compared to 9 pages for the instrument description and presentation of the methodology. Old section 4 is now divided in two parts to distinguish the methodology description (new section 2.3) and the discussion of the AOD and backscatter ratio results (new section 4). We agree however that the scientific discussion about the case studies in section 5 was poor and could be better detailed. It is now improved in the new version: new discussion of sunphotometer and lidar AOD comparison, new discussion of lidar ratio daily variability, more lidar vertical profiles are included in the analysis (Fig.10 to 12). A new introduction to section 5 is added (p.15 l.19-p.16 l.4 see hereafter) to clarify the goals, while the text in section 5.1 was significantly changed to emphasize the contribution to the AOD retrieval validation.

The introduction of section 5 now reads:

" In this section, we focus on the time periods with elevated AOD observed by the AERONET network above Tomsk in order to (1) compare the results of our AOD analysis with AERONET values during 48 h around the selected lidar profiles and with satellite data (MODIS or CALIOP) (2) identify the likely aerosol sources derived from the FLEXPART analysis with satellite observations (MODIS, IASI, CALIOP) in the source areas . Looking at Fig. 8, there are 5 time periods with sun-photometer AOD $>$ 0.25: mid-may 2015, end of may 2015, April 2016, mid-June 2016 and end of September 2016. We do not have enough lidar data for mi-June 2016. The end of September 2016 and mid-June 2015 cases both correspond to forest fire events, while end of may 2015 and April-2016 correspond to urban, flaring and dust emissions according to our FLEXPART analysis. Therefore the three time periods corresponding to periods A, B, C of Fig. 8 are analyzed in this section. The section 5.1 presents the daily variability of the lidar backscatter profiles and sun-photometer AOD, while the section 5.2 presents the analysis of satellite observations."

The instrument wavelength (808nm) might be more appropriate to study clouds than aerosols. The molecular signal at this wavelength is about 5 times less than at 532 nm and about 26 times less than 355nm making calibration very difficult (impossible during daytime as showed in Fig. 1). Moreover, the backscattering from the sub-micron part of the aerosol spectrum is almost negligible.

Of course we are aware of the drawbacks when using an IR laser source in a backscatter lidar and especially the lack of molecular signal detection during the day. Nevertheless these instruments are and will be used in monitoring network for cloud and aerosol owing to their cost, their size and their very stable laser transmitter. It is therefore useful to assess the aerosol measurement capabilities. We do not attempt to calibrate the lidar during daytime and 30 min. time integration of nighttime profiles is enough to detect the molecular signal in the upper troposphere (see Fig. 1) and lidar calibration is then possible. Regarding the sensitivity of the aerosol detection with a 808 nm lidar, the low molecular signal is a strong advantage to identify aerosol layers (layering seen for the case studies discussed in section 5 are good examples of this, see also the time/elevation plot for July 2nd 2015 shown below to illustrate the capabilities of the lidar to monitor aerosol layering in the free troposphere during the night). Even though the lidar is less sensitive to the sub-micronic part of the aerosol spectrum as pointed out by the reviewer, it is balanced by the large sub-micronic aerosol concentration in this region (e.g. see Paris et al. Atmos. Environ. 2009 https://doi.org/10.1016/j.atmosenv.2008.11.032). The rationales for using an IR lidar and the need for assessment of aerosol monitoring using a 808 nm lidar are now better explained in the introduction (see p.2 l.19-l.24).

FLEXPART model is used to speciate the aerosol layers and quantitatively assess the columnar LR to be used in the inversion. However, many parameters are assumed without giving

convincing explanations., i. e. A and B. How the results change if, for example, the number of released particles changes and also the altitude?

FLEXPART is used to sort the lidar profile according to a potential emission source. It is a much better approach than using simple back-trajectories. We have chosen an "aerosol like" tracer i.e. sensitive to dry deposition and scavenging to get a more realistic assessment of an aerosol source for long range transport through cloudy conditions. The parameters for wet scavenging have been chosen following previous studies using FLEXPART aerosol tracers (see Stohl 2013, Stohl 2012, Kriestiensen 2016). The results are usually weakly dependent on the number of particles released. It is of course strongly dependent on the altitude, this is why we select aerosol layer thickness sufficiently broad (>1 km) to minimize the sensitivity to strong differential advection, while being still specific of the airmass origin. I am not sure what kind of sensitivity studies are suggested by the reviewer. FLEXPART has been validated including aerosol tracer in many publications, so we do not wish to add more characterization of this tool in our work. More references to previous FLEXPART work are now given (Stohl et al. 2012, Kriestensen et al. 2016).

I suggest to put more emphasis on characterizing the source origins, transport processes, and vertical distributions of the aerosol layers on the region, possibly integrating the lidar observation with in-situ measurements, if available.

Unfortunately we do not have in-situ observations which can be discussed together with the lidar profiles, e.g. in section 5 describing the case studies. As stated in the answer to the first comment, we believe that the paper is now well balanced between the analysis of the aerosol sources using the lidar data (14 pages) and the presentation of the lidar data processing technique (9 pages). The paper would be incomplete if the data are discussed without explaining the procedure to derive the backscatter ratio and the AOD, especially for 808 nm micropulse lidar where the retrieval is not so straightforward. The new version is more balanced in the way proposed by the reviewer by making a better description and analysis of the lidar data for the three selected case studies (section 5) and splitting the old section 4 in two parts to distinguish the presentation of the methodology (section 2.3) and the discussion of the results (section 4). Along the same lines, the section 5.2 describing the satellite data analysis above the source region identified by FLEXPART is split in two parts to distinguish the description of the satellite data products (section 5.2.1) and the results (section 5.2.2) on the aerosol properties above the source region.

To be more specific the text changes in section 5 are the following:

- discussion of AOD comparison and vertical profiles daily variability: p.17 l.3-l.6 and p.18 l.11-l.12 and p.19 l.9-l.10
- discussion of S_{808} daily variability: p.18 l.2-l.10, and p.18 l.13-p.19 l.8 and p.19 l.13-p.20 l.2

Specific Comments:

Line 1, Abstract: The word climatology is not appropriate considering the total number of measurement.

Agreed although it is the first time such a large number of lidar profiles is discussed for Siberia. Climatology is replaced by "seasonal variability".

Line 8-9, Abstract: "it was complemented..." please rephrase as it is not clear. Do the authors mean ancillary ?

Sentence changed: "An aerosol source apportionment using the Lagrangian FLEXPART model is used in order to determine the lidar ratio of the remaining 48% of the lidar database".

Line 9-10, Abstract, The sentence is unclear. What exactly is compared? Attenuated backscattering with CALIPSO? or What? and what is it compared with MODIS and IASI data?

Agreed. The sentence now reads: "Backscatter ratio vertical profile, aerosol type and

AOD_{808} derived from micropulse lidar data are compared with sunphotometer AOD_{808} and satellite observations (CALIOP spaceborne lidar backscatter and extinction profiles, Moderate Resolution Imaging Spectroradiometer (MODIS) AOD550 and Infrared Atmospheric Sounding Interferometer (IASI) CO column) for three case studies corresponding to the main aerosol sources with $AOD_{808} > 0.2$ in Siberia."

Line 10, Pag. 2 the term "Radiative Forcing" is misused. I would change it into "Radiative Effects" Agreed

Line 13, Pag. 3 "continuous measurements of clouds and aerosols" again, this sentence lacks of precision. Please specify what it is measured.

Agreed replaced by "measurements of cloud and aerosol backscatter".

Line 6, Pag.4 "counts/s" Changed

Line 16 pag 4. How much is it the lidar blind region ? (overlap 0%).

The truly blind region is of the order of 100 m. Assessment of the AOD error when assuming a constant backscatter ratio below 100 m is added (see p.5 l.10-l.12).

Line 31 pag 4 supposing clear air at 2-4 km altitude is very risky

In fact this assumption is only for the first guess retrieval which is no longer used after the calibration of the daytime profile with the nighttime calibration factor. This sentence was removed as it has caused confusion. The calibration procedure has been clarified in section 2.2 (see p.6 l.1-l.4 and p. 7 l.3-l.5) and figure 4 now describes the lidar processing flowchart.

Figure 1 upper plot labels are very small and can't be read

Agreed Figure 1 upper panel has been changed

redPag. 5 bottom: fire is not a good choice, I would say biomass burning Agreed.

Line 8, Pag. 6 why 35%? any reference?

35% corresponds to the expected range for lidar ratio (35-60 sr) assuming that all the aerosol types can be encountered except the clean marine or dusty marine types. It is now better explained in section 2.2 and references to CALIPSO (Omar et al. 2009) and AERONET (Cattrall et al. 2005) have been added (p.7 l.3-l.5)

Line 1 Pag. 7 how much is the lidar sensible to the thermal stability?

Although the lidar box is thermally controlled, a gradual change of outside temperature remains the main source of gain variability (e.g. detuning of the detection interference filter). It is difficult to provide more direct quantitative results apart from the measured variability of the calibration factor discussed in section 4 and in Fig. 3.

Line 30 Pag. 9. How is retrieved the AOD at 808nm from 870nm?

The AERONET sunphotometer angstrom exponent (AE) measurement is used to estimate the AOD spectral variability between 808 nm and 870 nm. It was explained p.9 l.11-l.13.

Line 1 pag 10. how much is it the integration time to get a good molecular signal ? 30 mins are enough?

Yes 30 min. is enough during nighttime conditions since the statistical noise in the 30-min averaged PR2 is of the order of 7-8% at 9 km (e.g. see Fig. 1). Vertical averaging over 150 m at the reference altitude is also applied to derive the molecular signal to keep the uncertainty on the molecular signal below 3%. It is clarified in section 2.2 p.5 l.24-l.26, when we described the calibration method.

Figure 8. is 3.3 and 16.1 the time? it is pretty uncommon way...and the caption should be more detailed

We are not sure what the reviewer meant. Captions of figure 8 to 10 are now more detailed

Line 11 Pag. 19. The link is broken It is missing a discussion why the selected cases are

representative of the region

Corrected (l missing at the end of web address)

Line 13 Pag,. 22 Micropulse lidar in Sicard et al., 2016 is more suitable to study aerosol variability being at 532nm

Yes we agree if cost, eye-safe requirements, laser liftetime are not limiting factors in the lidar deployment (see the major issues discussion)

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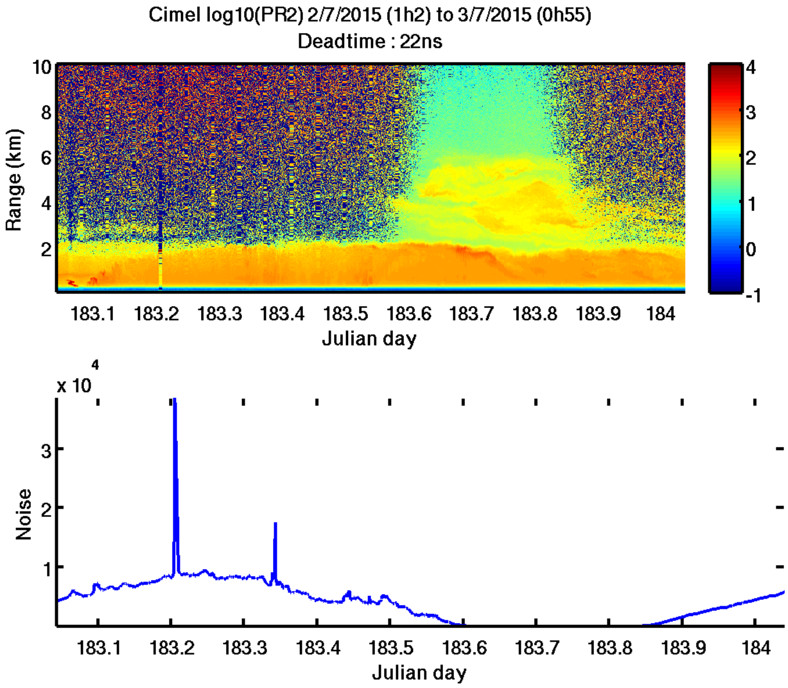

Fig. 1. Daily evolution of the vertical profiles of the log10 of the attenuated backscatter (upper panel) and the background noise due to solar radiation (lower panel) for July 2nd 2015