

Manuscript number: egusphere-2025-4208

MS type: Research article

Title: Retrievals of vertically resolved aerosol microphysical particle parameters with regularization from spaceborne Aerosol and Carbon dioxide Detection Lidar (ACDL)

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Iteration: Final response

We would like to express sincere gratitude to the Reviewers for the careful reading and providing comments. The point-to-point replies to the Referee comments are listed below.

Replies to RC2:

The manuscript represents the application of the regularization algorithm to the first spaceborne HSRL lidar ACDL, and enabling the retrievals of vertically resolved aerosol microphysical parameters. Although there is potential to improve the retrieval of the fine-mode particles, this work shows a valuable contribution by obtaining AMP from the spaceborne lidar and it is interesting. Before the manuscript can be publication, the following questions need to be addressed.

1. The author's choice of wavelengths in the inversion process differs from the commonly scheme ($3\beta+2\alpha$). Please explain the basis for the selection of the input data combination in this paper.

Responses:

Thanks for the comment regarding the wavelength selection in the inversion. The choice of wavelength combination is not arbitrary but is considered by the ACDL instrument architecture and to provide better constraint on coarse mode retrievals.

On an instrument base, in most previous studies, the wavelength combination at 355 nm, 1064 nm, and 1064 nm was employed because these wavelengths are available on ground-based systems. However, the ACDL onboard the AEMS satellite operates with laser wavelength at 532 nm, 1064 nm, and 1572 nm. On a physical base, the extinction and backscatter efficiencies at different wavelengths are sensitive to the particles with different size. Previous studies show that additional measurement channels help extend the retrieval size range (Veselovskii et al., 2004), and adding longer near-infrared wavelength can improve the coarse-mode AMP (Böckmann et al., 2024). Our simulation results confirm this behavior as shown in Fig. 2. Therefore, the optical data combination adopted directly follows the instrument design and all available wavelengths are considered in this work.

2. In the actual atmosphere, the refractive index of the atmosphere varies significantly due to changes of humidity and the type of aerosols, and there is a lack of discussion on the sensitivity of the inversion results to the choice of refractive index.

Responses:

We appreciate the reviewer concern. The aerosol complex refractive index m does vary greatly with its composition. And the sensitivity of inversion to the assumed m has been investigated in previous studies, which demonstrated that the uncertainties in m assumptions can be reduced by expanded wavelength combinations and other optimized constraints (Pérez-Ramírez et al., 2013; Pérez-Ramírez et al., 2020; Whiteman et al., 2018). In addition, we consider that uncertainties in m assumptions is not the main point we concerned, because in this work, we do not assume m to a single value for inversion, but adopt all possible m to retrieve distributions and then selected the acceptable solutions by the method described as Eq. (6) in Sec. 3. This approach is proposed by Müller et al. (Müller et al., 1999) and Veselovskii et al. (Veselovskii et al., 2002) and has been widely used (Di et al., 2018; Yan et al., 2019). And for the logical flow of the manuscript, we have added the relevant explain in Sec. 3 (lines 164) and the content is highlighted in blue font.

The revised version:

In Section 3 (lines 168-178):

“While the complex refractive index in the actual atmosphere is difficult to obtain, and the stand-alone lidar inversion is sensitive to the assumed complex refractive index. Thus, this work does not assume complex refractive index to a single value for inversion, but adopt all possible complex refractive index (for real parts of the refractive index, values of 1.3-1.6 are used, and for the imaginary part, values of 0.001-0.2 are chosen) to retrieve distributions and then selected the acceptable solutions by the method described as Eq. (6). This procedure has been widely used in previous studies (Di et al., 2018; Yan et al., 2019).”

3. Please provide a further explanation for the increase in the bimodal inversion errors in the simulation (volume concentration reaching 60%).

Responses:

We thank the reviewer for this valuable comment. The reason for the increase of the inversion errors in the bimodal can be summarized as the challenge in bimodal retrieval and the algorithm limitation.

Numerous studies have reached a consensus on the difficulty of the bimodal distribution retrieval and it's a challenge in the field. The inversion errors of the bimodal distribution are generally larger than the unimodal. Because with two modes, the kernel function for backscatter and extinction at a few wavelengths are overlapped in the large radius range, and leads to more degrees of freedom without any other constraints in the

retrieval (Müller et al., 1999; Veselovskii et al., 2002). Besides, the solution averaging process performed in the algorithm tends to influence the peak and the mode width of the reconstructed distribution (Veselovskii et al., 2004). And volume concentration scales with r^3 as a size-integrated parameters. Thus, the small reconstructed distribution errors will be accumulated, and the inversion error for the volume concentration will be larger than effective radius and the surface area concentration. This behavior has consistency with the results reported by Di et al. and Yan et al. Although the errors of bimodal volume concentration reach near the 60%, the 92% of which are controlled below 40% (as shown in Fig. 2). This error range is reasonable and acceptable compared with previous studies. We have added more discussion in Sec. 4.2.

The revised version:

In Section 4.2 (lines 240-258) and highlighted in blue font:

“For the bimodal distribution, variation of the scattering properties become more complicated and the inversion becomes more ill-posed. It is difficult to perform stable retrieval with a few kernels function (equal to the number of the input optical data at different wavelengths and the base function) due to insufficient optical constraints, because they overlap in radius range, which makes separate the fine and coarse mode hard. Regularization stabilizes the solution but tends to smooth the peaks and influence the mode width of the reconstructed bimodal distribution near the retrieval radius edge (as shown in Fig. 1). Thus, the reconstruction results of the bimodal distribution show more differences from the original APSD, and leads to an increased inversion errors for AMP calculated based on Eq. (8)-(10). Besides, for both the unimodal and the bimodal distribution, the errors for volume concentration are slight larger than the errors for effective radius as shown in Fig. 2, among the AMP, volume concentration is a direct integral of APSD (Eq. (10)) and the effective radius is a ratio of integrals (Eq. (8)). Thus, the small reconstructed distribution errors will be accumulated, and the inversion error for the volume concentration will be larger than effective radius. This behavior has consistency with the results reported by Di et al (Di et al., 2018).”

4. There is a lack of quantitative description of the ACDL data errors shown in Fig. 10, as well as the other two sets of comparison data.

Responses:

Thanks for pointing out this shortcoming. We have added a relevant text in Sec. 5.2 to provide a quantitative and clear description.

The revised version:

In Section 5.2 (lines 401-412) and highlighted in blue font:

“In order to verify the inversion results of ACDL, the aerosol effective radius results obtained from the inversion are compared with the effective radius of four

typical aerosols given by LIVAS (Amiridis et al., 2015) and CALIPSO (Omar et al., 2009; Omar et al., 2005). And the comparison results are shown in Fig. 10. For urban aerosol, effective radius is 0.28 μm from LIVAS and 0.26 μm from CALIPSO, while retrieved results from ACDL is $0.47 \pm 0.127 \mu\text{m}$. For smoke aerosol, the effective radius results are 0.26 μm , 0.36 μm , and $0.57 \pm 0.065 \mu\text{m}$ from LIVAS, CALIPSO, and ACDL, respectively. The effective radius for dust is 0.65 μm from LIVAS, 0.36 μm from CALIPSO and $0.61 \pm 0.075 \mu\text{m}$ from ACDL. The results for marine aerosol are 0.75 μm , 0.93 μm , and $0.83 \pm 0.083 \mu\text{m}$, respectively.”

5. It would be better to add the display of parameters for the ACDL system.

Responses:

Thanks for the valuable suggestion. We have added a table of ACDL parameters in Sec. 2.1 to provide more information for the instrument.

The revised version:

In Sec. 2.1 (line 96) and highlighted in blue font:

“Table 1 shows the main parameters of the ACDL system.”

Table 1. Main parameters of the ACDL system

Parameters	Value		
Laser wavelength	532 nm	1064 nm	1572 nm
Laser energy	150 mJ (532 nm)	110 mJ (1064 nm)	75 mJ (1572 nm)
Laser repetition rate	20 Hz		
Laser pulse width	$\leq 50 \text{ ns}$		
Divergence angle after	$\leq 0.1 \text{ mrad}$		
laser beam expansion			
Field of view	$\leq 0.2 \text{ mrad}$		
Telescope aperture	1000 mm		
Data acquisition	50 M/s		

Amiridis, V., Marinou, E., Tsekeri, A., Wandinger, U., Schwarz, A., Giannakaki, E., Mamouri, R., Kokkalis, P., Biniotoglou, I., Solomos, S., Herekakis, T., Kazadzis, S., Gerasopoulos, E., Proestakis, E., Kottas, M., Balis, D., Papayannis, A., Kontoes, C., Kourtidis, K., Papagiannopoulos, N., Mona, L., Pappalardo, G., Le Rille, O., and Ansmann, A.: LIVAS: a 3-D multi-wavelength aerosol/cloud database based on

CALIPSO and EARLINET, *Atmos. Chem. Phys.*, 15, 7127-7153, doi:10.5194/acp-15-7127-2015, 2015.

Böckmann, C., Ritter, C., and Graßl, S.: Improvement of Aerosol Coarse-Mode Detection through Additional Use of Infrared Wavelengths in the Inversion of Arctic Lidar Data, *Remote Sensing*, 16, 10.3390/rs16091576, 2024.

Di, H., Wang, Q., Hua, H., Li, S., Yan, Q., Liu, J., Song, Y., and Hua, D.: Aerosol Microphysical Particle Parameter Inversion and Error Analysis Based on Remote Sensing Data, *Remote Sensing*, 10, 10.3390/rs10111753, 2018.

Müller, D., Wandinger, U., and Ansmann, A.: Microphysical particle parameters from extinction and backscatter lidar data by inversion with regularization: theory, *Appl. Opt.*, 38, 2346-2357, doi:10.1364/AO.38.002346, 1999.

Omar, A. H., Won, J.-G., Winker, D. M., Yoon, S.-C., Dubovik, O., and McCormick, M. P.: Development of global aerosol models using cluster analysis of Aerosol Robotic Network (AERONET) measurements, *J. Geophys. Res.*, 110, doi:10.1029/2004JD004874, 2005.

Omar, A. H., Winker, D. M., Vaughan, M. A., Hu, Y., Trepte, C. R., Ferrare, R. A., Lee, K.-P., Hostetler, C. A., Kittaka, C., Rogers, R. R., Kuehn, R. E., and Liu, Z.: The CALIPSO Automated Aerosol Classification and Lidar Ratio Selection Algorithm, *J. Atmos. Oceanic Technol.*, 26, 1994-2014, doi:10.1175/2009JTECHA1231.1, 2009.

Pérez-Ramírez, D., Whiteman, D. N., Veselovskii, I., Kolgotin, A., Korenskiy, M., and Alados-Arboledas, L.: Effects of systematic and random errors on the retrieval of particle microphysical properties from multiwavelength lidar measurements using inversion with regularization, *Atmospheric Measurement Techniques*, 6, 3039-3054, 10.5194/amt-6-3039-2013, 2013.

Pérez-Ramírez, D., Whiteman, D. N., Veselovskii, I., Korenski, M., Colarco, P. R., and da Silva, A. M.: Optimized profile retrievals of aerosol microphysical properties from simulated spaceborne multiwavelength Lidar, *Journal of Quantitative Spectroscopy and Radiative Transfer*, 246, 10.1016/j.jqsrt.2020.106932, 2020.

Veselovskii, I., Kolgotin, A., Griaiznov, V., Müller, D., Franke, K., and Whiteman, D. N.: Inversion of multiwavelength Raman lidar data for retrieval of bimodal aerosol size distribution, *Applied Optics*, 43, 1180-1195, 10.1364/AO.43.001180, 2004.

Veselovskii, I., Kolgotin, A., Griaiznov, V., Müller, D., Wandinger, U., and Whiteman, D. N.: Inversion with regularization for the retrieval of tropospheric aerosol parameters from multiwavelength lidar sounding, *Appl. Opt.*, 41, 3685-3699, doi:10.1364/AO.41.003685, 2002.

Whiteman, D. N., Pérez-Ramírez, D., Veselovskii, I., Colarco, P., and Buchard, V.: Retrievals of aerosol microphysics from simulations of spaceborne multiwavelength lidar measurements, *Journal of Quantitative Spectroscopy and Radiative Transfer*, 205, 27-39, 10.1016/j.jqsrt.2017.09.009, 2018.

Yan, Q., Di, H., Zhao, J., Wen, X., Wang, Y., Song, Y., and Hua, D.: Improved algorithm of aerosol particle size distribution based on remote sensing data, *Applied Optics*, 58, 10.1364/ao.58.008075, 2019.