Response to Anonymous Referee #1

MS No.: amt-2023-219
MS type: Research article
Title: Aerosol Optical Properties Measurement using the Orbiting High Spectral Resolution Lidar onboard DQ-1 Satellite: Retrieval and Validation
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Dear Professors:

We express our sincere gratitude to the anonymous referee for dedicating his/her valuable time to scrutinize our manuscript and offer constructive feedback and suggestions. The insightful comments have proven instrumental in enhancing the overall quality of our manuscript. Every comment has been meticulously considered, leading us to implement substantial revisions in our manuscript. We also asked native English colleagues to double-check our language. Our heartfelt thanks extend to both the Editor and the referee for their invaluable suggestions, which significantly contributed to the refinement of the earlier version of our manuscript. Hopefully, the revised manuscript will be considered to be published in Atmospheric Measurement Techniques.

General comments and major points

Point 1: Abstract: DQ-1 consists of more than just the lidar

Response 1: We apologize for our wording here. In addition to Aerosol and Carbon Detection Lidar (ACDL), the satellite also includes Wide Spectral Imager (WSI), Participate Observing Scanning Polarimeter (POSP), Environment Monitoring Instrument-2 (EMI-2), and Directional Polarization Camera-2 (DPC-2). the HSRL system is one part of ACDL. Corresponding modifications have been made to the manuscript, and the corresponding changes are displayed in red font.

Line 13: The Atmospheric Environment Monitoring Satellite (AEMS), also called DaQi-1 (DQ-1), was launched in April 2022, one of its main payloads is the High Spectral Resolution Lidar (HSRL) system.

Point 2: Abstract: Linear depolarization ratio?

Response 2: Thank you for bringing this matter to our attention. DQ-1 retrieved the linear polarization of the aerosol, and we have made modifications to the terms in the abstract at:

Line 17: This method has retrieved the aerosol linear depolarization ratio, backscatter coefficient, extinction coefficient, and optical depth.

Point 3: l. 30: Probably 10^2 is meant here. 10 nm as maximum is certainly wrong. And in principle there is no lower limit until you reach the molecular level at about 0.1 nm.

Response 3: We apologize for this significant error, the value has been corrected at:

Line 30: Aerosols are tiny solid and liquid particles suspended in the atmosphere, an atmospheric aerosol particle typically ranges from 0.01 to 10 μm in diameter.

Point 4: l. 38: I would not assume results from ground-based lidar systems to be more accurate in general. Especially when e.g. assuming daytime measurements with Fernald/Klett algorithms and no further information of the lidar ratio or the long integration time needed for night-time Raman measurements.

Response 4: Thank you for pointing out this issue. Due to the use of traditional Fernald methods for retrieval in ground-based lidars such as MPLNET, it should not be stated here that their observations are accurate. Our comparison with MPLNET is qualitative analysis. The sentences have been modified at:

Line 38: There are several advantages of ground-based lidar: easy maintenance of the instrument, long-term stable observation of specific areas (Mattis et al., 2004; Pitari et al., 2013).

Point 5: l. 39: Also compared to what; airborne or spaceborne measurements? 'Additionally, comparing…' This sentence seems to be at the wrong place here.

Response 5: We are sorry about our wording here. What we want to express is that ground-based data can be compared with spaceborne and airborne data.

Line 39: Furthermore, it is beneficial to validate spaceborne and airborne measurements with ground-based lidar systems.

Point 6: l. 65: Was fuel consumption really the reason? I also heard of solar panel degradation. Maybe you should add a reference.

Response 6: The source of this information is the Calipso webpage of LARC (https://www-calipso.larc.nasa.gov/), its original text is:" *Fuel reserves are now exhausted*, and in its decaying orbit the satellite can no longer generate sufficient power to operate the science instruments." We have added this reference to the manuscript at:

Line 65: Due to fuel consumption (Langley Research Center, 2024), CALIPSO was retired in August 2023, a well-established and developed new-generation spaceborne Lidar is needed to replace CALIPSO for global aerosol observation.

The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO): https://www-calipso.larc.nasa.gov/, last access: Jan 2nd.

Point 7: l. 73: According to the latest developments AOS will not incorporate an HSRL channel. But this may change again if NASA sees the benefit of the DQ-1 data.

Response 7: Thank you for pointing out this issue. According to the literature cited in this sentence, AOS program have studied the scientific value of spaceborne HSRL systems. We have modified the manuscript, the corresponding changes are displayed in red font.

Line 73: Furthermore, under the leadership of NASA, the Atmosphere Observing System (AOS) international program analyzes the additional value provided by the spaceborne HSRL system. This research has shown that the results of spaceborne HSRL systems are more accurate than the results of traditional elastic backscatter lidar in three different cases (Cornut et al., 2023).

Point 8: l. 83: Does duel-polarization mean duel wavelength?

Response 8: The DQ-1 HSRL system only includes lasers with a wavelength of 532.245 nm. The meaning of "dual" refers to parallel polarization and perpendicular polarization.

Point 9: l. 108: To which line catalogue corresponds this numbering? Please give a reference.

Response 9: We apologize for our negligence, the reference has been added to the manuscript at:

Line 108: The laser beam of the HSRL system has a wavelength of 532.245 nm, a pulse repetition frequency of 40 Hz, and the absorption line of iodine molecules corresponds to line 1110 (Weibiao et al., 2023).

Weibiao, C., Jiqiao, L., Xia, H., Huaguo, Z., Xiuhua, M., Yuan, W., and Xiaopeng, Z.: Lidar Technology for Atmosphere Environment Monitoring Satellite, Aerospace Shanghai (Chinese & English), 40, 13-20, 10.19328/j.cnki.2096-8655.2023.03.002, 2023.

Point 10: l. 110: What exactly is meant by 'categorized' and 'adjusted' here?

Response 10: We are sorry about our wording and mistake here. What we want to express is that the purpose of our processing is to normalize these two pulses. Corresponding revision has been made to the manuscript at:

Line 110: Both of the pulses are normalized prior to the retrieval process.

Point 11: l. 118: 25 db is quite low for an Iodine filter. Is this limited by the iodine vapor pressure or is there some spectral impurity of the laser? And how stable is this value, as it has to be considered in the retrieval?

Response 11: Thank you for raising this important question. The transmittance of the iodine filter is related to its temperature and pressure. The temperature and pressure of the iodine filter on the DQ-1 HSRL are controlled within a certain range to ensure stable transmittance.

25 db is sufficient to filter out the Mie scattering for subsequent retrieval. To illustrate this issue, we have selected a representative profile to analyze its filtering effect. Figure 1 showcases an attenuated backscatter profile. The red line represents the unfiltered signal, the green line represents the filtered signal, and the blue line represents the molecular backscatter signal. The unfiltered signal displays the echo signal of the cirrus at an altitude of 13-15 km. The signals of cirrus contain strong Mie scattering signals, the filtered signal only contains molecular backscatter, without the Mie scattering signal. Similarly, clouds at 5-6 km are only observed in the unfiltered signal. At an altitude of 3 km, the signal cannot penetrate thick cumulus clouds, resulting in signal attenuation below this altitude. The filtered signal is more in line with the molecular scattering, the signals from clouds and aerosols have been filtered out.

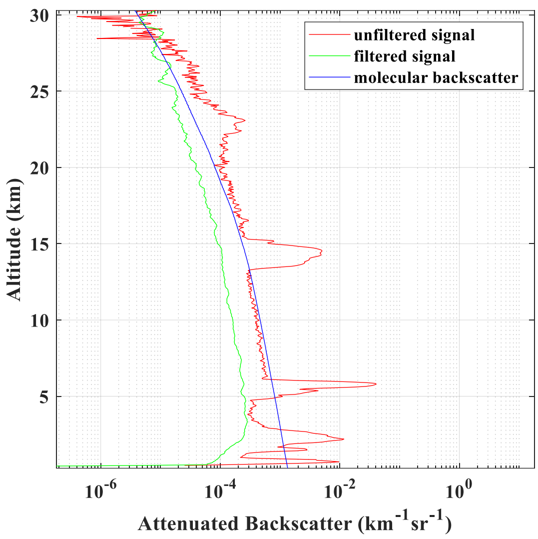
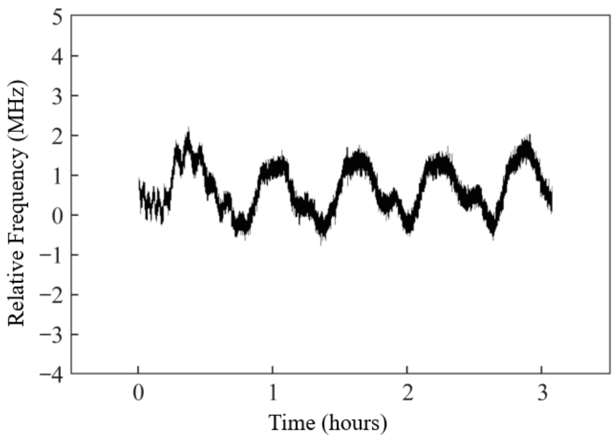


Figure 1 Attenuated backscatter profile

The stability of this value is related to the stability of the laser frequency. Before the satellite was launched, the stability of the seed laser was tested, and the results are shown in Figure 2, the standard deviation of frequency variation within 3 hours is 0.8 MHz@rms (Weibiao et al., 2023). The stability of the frequency can also ensure the stability of the suppression ratio of the iodine filter (Dong et al., 2018).



Fugure 2 Frequency stabilization measurement by the 1064 nm seeder laser

Point 12: l.125: 'A and B…' It is not exactly clear what is meant here with interleaved.

Response 12: We are sorry about our mistake here. The sentences here are revised to:

Line 125: To improve the signal-to-noise ratio of the original data, the two pulses have been normalized and averaged.

Point 13: l. 125: compare = achieve?

Response 13: We apologize for our previous wording choice. 'achieve' is a more accurate verb to use.

Line 125: To achieve the design's horizontal resolution of 20 km, we used 48 sets to configure the pulse averaging iterations, and the vertical resolution is 48 meters.

Point 14: P.6, Eq 2.8: This is a replication of Eq. 2.6. Please delete.

Response 14: We apologize for our mistake. We have deleted the incorrect formula. All formulas have been rechecked.

Point 15: l. 236f: Why should this be a mixture, here directly of the desert? In the retrieval the dust plume looks extremely homogenous, with no sign of mixing; And 50 sr does not really point to mixed dust.

Response 15: According to the literature, due to the aerosol depolarization ratio observed by DQ-1 being 0.2, it belongs to the range of dust. Considering your comments, we will no longer refer to it as a mixed dust.

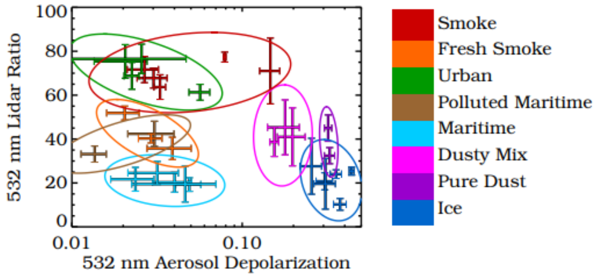


Figure 3 Classification model of HSRL (Burton et al., 2012).

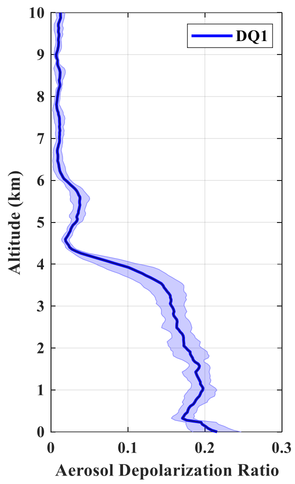


Figure 4 Aerosol depolarization ratio mean profile of 20°N to 22°N measured by DQ-1 on June 6, 2022.

The corresponding modifications were made to the manuscript at:

Line 236: The value of the depolarization ratio at low altitude obtained from DQ-1 is 0.2, demonstrating the nature of dust.

Line 244: The advantage of the DQ-1 HSRL system is that it can retrieval the lidar ratio without assumptions, which is significantly different from CALIPSO. DQ-1 indicate that the lidar ratio of aerosol particles is around 40 sr, describing the characteristics of aerosols, consistent with Calipso's aerosol type.

Line 317: On July 3rd, measurements over West Africa indicated a lidar ratio distribution centered around 50 sr and depolarization ratio values within the range of 0.3 to 0.4, representing dust.

Point 16: l. 243ff: What is meant here by laser energy attenuation? A smaller laser energy does not alter the mean profile.

Response 16: Due to CALIPSO's prolonged in orbit operation, laser energy attenuation causes diminished signal-to-noise ratio, leading to more noise signals within the echo signal and consequently, increased measurement inaccuracies. As depicted in Figure 5, the SNR profile of DQ-1 is shown within a spatial region identical to that of CALIPSO. Within the latitude range of 40°N to 10°N, the signal-to-noise ratio of DQ-1 measures 60, while CALIPSO measures a lower value of 20. The noise signal of CALIPSO affecting the retrieval results, resulting in the depolarization ratio results exceeding the credible range.

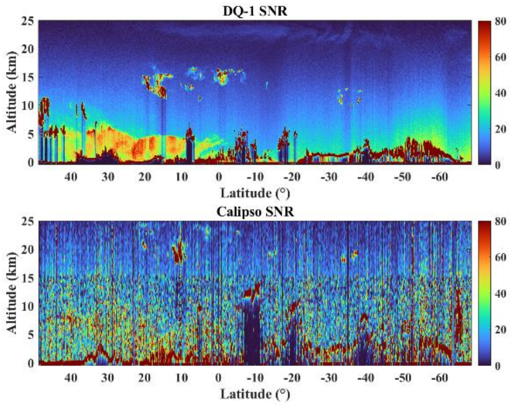


Figure 5 SNR of DQ-1 and CALIPSO total attenuated backscatter

Point 17: l.245: For CALIPSO this value comes from a database and is not measured.

Response 17: We apologize for our negligence. We have acknowledged this issue in the relevant section of the article. Due to the lack of accurate lidar ratio results at present, we chose to compare with CALIPSO. The lidar ratio of DQ-1 was only qualitatively compared with CALIPSO. The corresponding modifications were made to the manuscript at:

Line 244: The advantage of the DQ-1 HSRL system is that it can retrieval the lidar ratio without assumptions, which is significantly different from CALIPSO. DQ-1 indicate that the lidar ratio of aerosol particles is around 40 sr, describing the characteristics of dust aerosols, consistent with Calipso's aerosol type.

Point 18: l. 256: The sentence says the same as the previous one.

Response 18: We apologize for our mistake. The corresponding modification has been made to manuscript at:

Line 254: This comparison has three surface types: land, ocean, and coastal regions. Profile-averaged findings inside a circle with a radius of 100 kilometers, centered on MPLNET stations, were explicitly chosen for DQ-1 data. For MPLNET data, we utilized the average MPLNET profile within 15 minutes of DQ-1 transit.

Point 19: l. 319: Particle depolarization ratio would be much more valuable;
Figure 9: What sort of depolarization ratio is shown? According to the main text it is volume depolarization but particle depolarization would be more interesting.
l., 320: If this is volume depolarization ratio, like stated above, this is not necessarily the case. The constant lidar ratio does not indicate a large amount of mixing. Please provide aerosol particle depolarization. Maybe in the instrument section a paragraph should be added on how the depolarization measurements are calibrated and how large a possible instrument related depolarization is.

Response 19: Thank you for pointing out this issue. We have changed to using the particulate depolarization ratio to analyze the African dust instead of the volume depolarization ratio. After considering your opinion and our discussion, we also believe that this does not reflect the characteristics of mixed dust.

On the issue of the possible instrument related depolarization. The clean atmosphere at high altitudes only contains atmospheric molecules. Retrieving the depolarization ratio of atmospheric molecules at high altitudes can determine whether there are possible instrument related errors. We have chosen a profile illustrating a high-altitude depolarization ratio result, as depicted in Figure 6. The results show that DQ-1 retrieved the molecular depolarization ratio of 1%, which is consistent with the literature (Young, 1982; Rowell et al., 1971), so we believe that the instruments are insufficient to cause errors in the retrieval results.

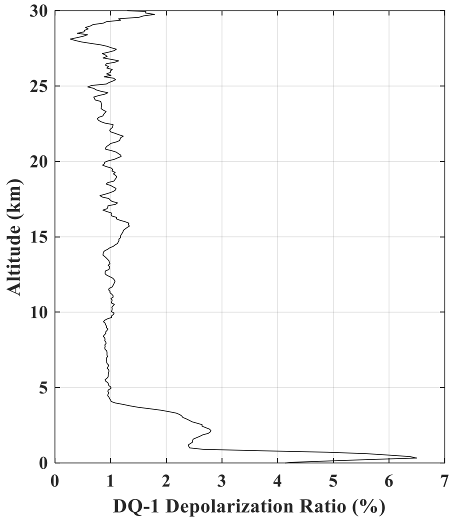


Figure 6 Profile of DQ-1 depolarization ratio

The system calibration regarding the depolarization ratio has been added. The corresponding modification has been made to the manuscript at:

Line 139:

$$B^{\perp}(r) = \frac{P(r)r^2}{P_0\eta^{\perp}AL}[\beta_m^{\perp}(r) + \beta_a^{\perp}(r)] \times exp\left\{-2\int_0^r [\alpha_m(r) + \alpha_a(r)]\,dr\right\} \tag{2.1}$$

$$B_C^{\parallel}(r) = \frac{P(r)r^2}{P_0\eta_C^{\parallel}AL}[\beta_m^{\parallel}(r) + \beta_a^{\parallel}(r)] \times exp\left\{-2\int_0^r [\alpha_m(r) + \alpha_a(r)]\,dr\right\} \tag{2.2}$$

$$B_H^{\parallel}(r) = \frac{P(r)r^2}{P_0\eta_H^{\parallel}AL}[T_m(r)\beta_m^{\parallel}(r) + T_a(r)\beta_a^{\parallel}(r)] \times exp\left\{-2\int_0^r [\alpha_m(r) + \alpha_a(r)]\,dr\right\} \tag{2.3}$$

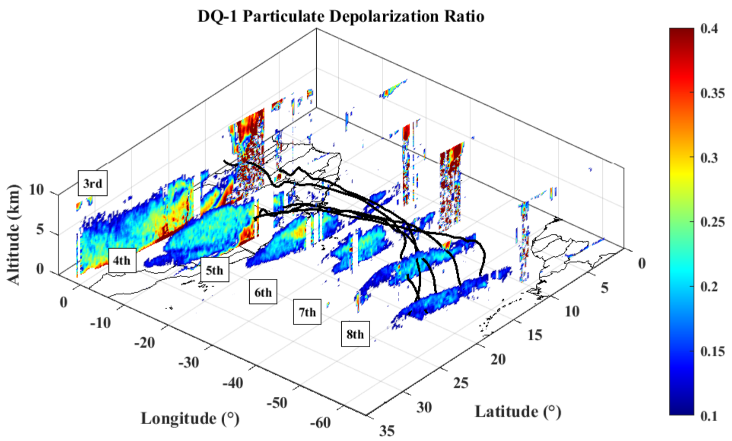
Line 144: $P(r)$ represents the power of the laser echo signal at distance r. P_0 represents the emitting power of the laser, η represents the optical efficiency of the corresponding receiving channel, A represents the aperture of the telescope, and L stands for the half of the pulse spatial transfer length, where L is calculated as $L = c\Delta t/2$, with c representing the speed of light and Δt denoting the pulse duration. System correction has been implemented to ensure that the data is solely contingent upon atmospheric conditions. $\beta_m(r)$ and $\beta_a(r)$ represents the backscatter coefficient of molecules and aerosols respectively, $\alpha_m(r)$ and $\alpha_a(r)$ represents the molecular and the aerosol extinction coefficients. The molecular backscatter coefficient and extinction coefficient are calculated by the S6 molecular model using the data of temperature and pressure provided by ERA5.

Line 317: On July 3rd, measurements over West Africa indicated a lidar ratio distribution centered around 50 sr and the particulate depolarization ratio values within the range of 0.25 to 0.4, representing dust.

Line 319: During the transport process, the value of the lidar ratio was constant at 50 sr, while the particulate depolarization ratio was reduced from 0.25 to 0.15.

Line 325: DQ-1 observed that as these aerosols were transported, their altitude, backscatter coefficient, and particulate depolarization ratio decreased at the lidar ratio's constant value.

Line 593 Figure 9c:



Point 20: l.333: The backscatter coefficient does not depend on laser energy, only the raw signals. So, there is nothing to correct.

Response 20: Thank you for pointing out this issue and we are sorry for our wording here. The correction we made refers to the correction based on molecular scattering at the reference height, and it is inappropriate to refer it to energy correction. The corresponding modification has been made to the manuscript at:

Line 331: As DQ-1 data is available from June to December 2022, we substituted data from February to June 2022 with CALIPSO data. Figure 10 presents the observed attenuated backscatter coefficient from January to December 2022 within the stratosphere over the South Atlantic Ocean, using both CALIPSO and DQ-1.

Point 21: P.12, l. 344: I would recommend to talk of volcanic aerosol not volcanic ash. The ash sediments out quite fast. What goes into the stratosphere are mostly condensated gases like H_2O or H_2SO_4 etc.

Response 21: Thank you for pointing out this issue. We accepted your comment and have made relevant modifications at:

Line 25: We use the DQ-1 dataset to initially investigate the transport processes of the Saharan dust and the South Atlantic volcanic aerosols.

Line 98: We use data from DQ-1 to analyze the transport processes of Saharan dust and South Atlantic tropospheric volcanic aerosol.

Line 330: DQ-1 observations over the South Atlantic have revealed various effects and distribution of volcanic aerosol in the stratosphere.

Line 340: By May 1st, due to insufficient laser energy, CALIPSO received weak volcanic aerosol backscatter signals, making them difficult to distinguish from system noise.

Line 343: Due to the diffusion of volcanic aerosols in the stratosphere and the advantages in laser energy of the DQ-1 system, the results from DQ-1 indicate a broader distribution range of volcanic aerosols. By August 1st, volcanic aerosols had extended southward to 50° S latitude, with an altitude of less than 20 km.

Point 22: P.13, l. 353: It has not been shown that the outcome of the depolarization ratio from DQ-1 is more reliable. No analyses of the systematical error of the depolarization measurements have been provided.

Response 22: We apologize for this oversight. The reliability of DQ-1's depolarization ratio depends on the analysis of system errors. The corresponding modification has been made to the manuscript at:

Line 353: The aerosol optical parameters obtained from DQ-1 has been validated against the product of CALIPSO and molecular backscatter coefficients. The results indicated that DQ-1 exhibited a higher signal-to-noise ratio and conforms to the results of trends in molecular scattering.

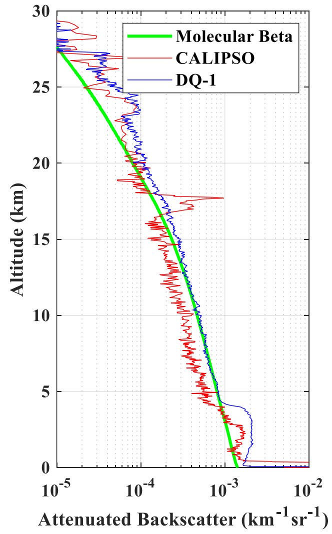
Point 23: Figure 4: The profile (e) for Calipso seems wrong and also does not fit to the data given in the plot (b). In the profile plot (e) the data of Calipso drops below 10^-5 above 14 km. But this behavior is not present in (b) where ist stays between 10^-3 to 10^-4.
l. 215: There seems to something wrong with the CALIPSO backscatter profile. See remark at the plot.

Response 23: We apologize for the mistake. After a comprehensive inspection, the height axis of Figure 4e is incorrect. The current image has been modified correctly, and the corresponding descriptions and analysis in the manuscript has been modified at:

Line 215: The raw signals of the DQ-1 and the CALIPSO align with the molecular scattering profile.

Line 223: In conclusion, the two satellites give consistent raw data results in close orbits, DQ-1 operating at a higher resolution, achieves a better signal-to-noise ratio.

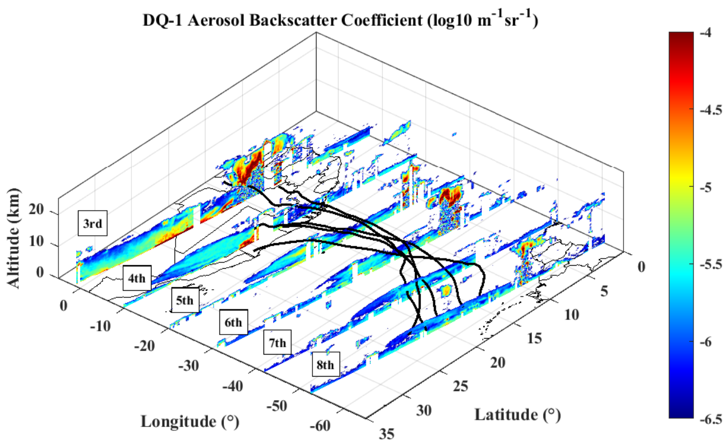
Line 550 Figure 4e:



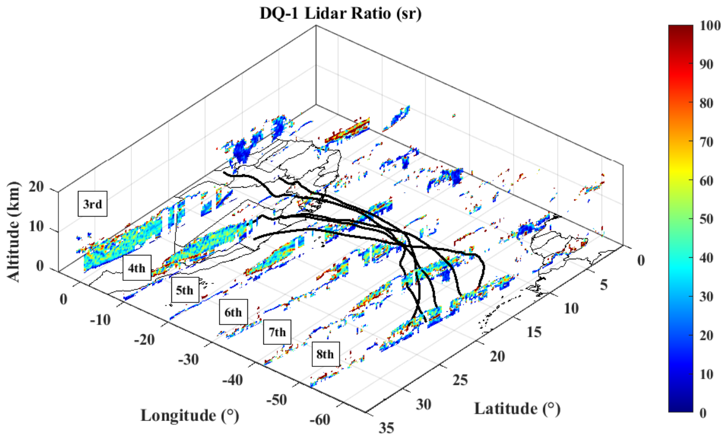
Point 24: P.29, Figure 9: The figures are too small to see all details. I would suggest to put them below each other and enlarge them to fill the whole page width.

Response 24: We apologize for neglecting the size of the figures. Corresponding modifications to the figures in:

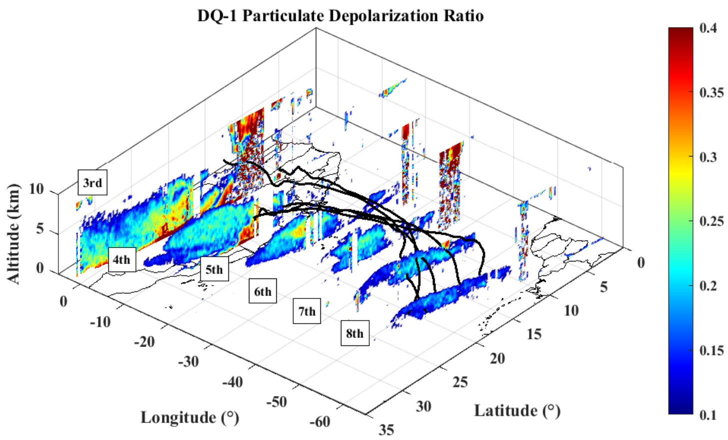
Line 591: Figure 9a:



Line 591: Figure 9b:



Line 591: Figure 9c:



Point 25: P.30, Table 1: What is missing here is the optical efficiency of the receiver optics including sun-light filter and the quantum efficiency of the detector. The measurement accuracy depends on the atmosphere probed, i.e. on altitude and aerosol content and also on ambient light conditions. So, one number is not characterizing this well. Furthermore, horizontal resolution would be a better wording than parallel resolution.

Response 25: Thank you very much for your questions and suggestions. We have added the necessary parameters to Table 1, the corresponding modification are made to Table 1 at:

Line 602 Table 1:

Table 1. Main parameters of the DQ-1 HSRL system (Dong et al., 2018; Weibiao et al., 2023).

Parameter	Value
Laser Wavelength	532.245nm
Laser Energy	≥150mj
Laser Frequency Stability	1MHz@10000s
Laser repetition frequency	40 Hz
Telescope aperture	1000 mm

Field of view	0.2 mrad
Broadband bandpass filter	0.45 nm
Narrowband FP filter	30 pm
HSRL filters	iodine vapor filter, 1110 line aerosol signal suppression ratio ≥ 25 dB
Overall optical efficiency (excluding iodine filter)	0.16 at parallel polarized channel 0.561 at perpendicular polarized channel 0.375 at high spectral resolution channel
Quantum efficiency of the detector	40%
Measurement accuracy	15% uncertainty with 20km horizontal resolution

The above is all our responses to you. Thank you very much for your attention and time, we would be glad to respond to any further questions and comments that you may have.

Yours sincerely,

Chenxing Zha, Lingbing Bu, Zhi Li, Qin Wang, Ahmad Mubarak, Pasindu Liyanage, Jiqiao Liu, and Weibiao Chen.

Reference

Burton, S. P., Ferrare, R. A., Hostetler, C. A., Hair, J. W., Rogers, R. R., Obland, M. D., Butler, C. F., Cook, A. L., Harper, D. B., and Froyd, K. D.: Aerosol classification using airborne High Spectral Resolution Lidar measurements – methodology and examples, Atmos. Meas. Tech., 5, 73-98, 10.5194/amt-5-73-2012, 2012.

Dong, J., Liu, J., Bi, D., Ma, X., Zhu, X., Zhu, X., and Chen, W.: Optimal iodine absorption line applied for spaceborne high spectral resolution lidar, Appl. Opt., 57, 5413-5419, 10.1364/AO.57.005413, 2018.

Mattis, I., Ansmann, A., Müller, D., Wandinger, U., and Althausen, D.: Multiyear aerosol observations with dual-wavelength Raman lidar in the framework of EARLINET, Journal of Geophysical Research: Atmospheres, 109, https://doi.org/10.1029/2004JD004600, 2004.

Pitari, G., Di Carlo, P., Coppari, E., De Luca, N., Di Genova, G., Iarlori, M., Pietropaolo, E., Rizi, V., and Tuccella, P.: Aerosol measurements at L'Aquila EARLINET station in central Italy: Impact of local sources and large scale transport resolved by LIDAR, Journal of Atmospheric and Solar-Terrestrial Physics, 92, 116-123, https://doi.org/10.1016/j.jastp.2012.11.004, 2013.

Rowell, R. L., Aval, G. M., and Barrett, J. J.: Rayleigh–Raman Depolarization of Laser Light Scattered by Gases, The Journal of Chemical Physics, 54, 1960-1964, 10.1063/1.1675125, 1971.

Weibiao, C., Jiqiao, L., Xia, H., Huaguo, Z., Xiuhua, M., Yuan, W., and Xiaopeng, Z.: Lidar Technology for Atmosphere Environment Monitoring Satellite, Aerospace Shanghai (Chinese & English), 40, 13-20, 10.19328/j.cnki.2096-8655.2023.03.002, 2023.

Young, A. T.: Rayleigh scattering, Physics Today, 35, 42-48, 10.1063/1.2890003, 1982.