Assessing the Impact of Volume Depolarization Ratio on GRASP Aerosol Retrievals: A comparative study using Polly^{XT} Raman Lidar and Sun-photometer Data in Limassol, Cyprus

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Abstract: The impact of volume depolarization ratio (VDR) on aerosol optical and microphysical properties columnar and vertically obtained with the GRASP (Generalized Retrieval of Aerosol and Surface Properties) algorithm is investigated. Identical daytime input datasets used to evaluate two retrieval configurations with and without VDR, aiming to improve the vertical characterization of non-spherical components. The analysis is based on the Polly^{XT} Raman-Polarization Lidar of the Cyprus Atmospheric Remote Sensing Observatory (CARO), operated by the Eratosthenes Centre of Excellence and the inversion products from the co-located sun/sky photometer performed in Limassol, Cyprus. Independent Lidar and sun-photometer products, vertical profiles of extinction, backscatter coefficients, columnar Aerosol optical depth (AOD) and Single Scattering Albedo (SSA) evaluate GRASP retrievals of the two approaches to assess agreement and consistency. Integrating VDR significantly improved the results, specifically the vertical consistency of the Backscatter coefficient at 532 nm compared to lidar data, though minor biases were noted in the Extinction profile. While Columnar AOD indicated good agreement in both configuration modes, the VDR is a critical constraint for non-spherical particles.

1. Introduction

Synergies of active and passive atmospheric remote sensing instruments can be a powerful approach for improving the characterization of the atmospheric composition. The complementary strengths of active sensors, such as Lidars and passive instruments as well as radiometers, are becoming technically feasible to acquire more accurate and vertically resolved information on aerosols in the atmosphere [1, 2, 3].

GRASP is a highly flexible inversion algorithm applicable in various disciplines, including observations from both active and passive remote sensing methods. GRASP numerical inversion algorithm follows a statistically optimized multi-term least squared method (LSM) and atmospheric radiation modelling [4]. GRASP

Synergistic data from multi-wavelength Lidar and sun/sky photometer observations used previously in Lidar-Radiometer Inversion Code (LIRIC) [3] and Generalized Aerosol Retrieval from Radiometer and Lidar Combined data (GaRRLiC)/GRASP [1, 2, 5] algorithms. LIRIC algorithm showed [3] that combining elastic lidar with VDR, and radiometer observations can characterize vertically mixtures of aerosol layers of fine, coarse spherical and coarse non-spherical particles. A previous study that incorporated VDR information from Lidar to GRASP algorithm, showed that the retrievals demonstrated better agreement with MPLNET and sun-photometer observations at night, while better agreement was showed for daytime retrievals when the VDR excluded [5].

Building on these findings, this study aims to evaluate the impact of the VDR from Lidar on GRASP aerosol retrievals in Limassol, Cyprus using Polly^{XT} Raman Lidar and sun-photometer measurements.

2. Instrumentation & Data

Cyprus Atmospheric Remote Sensing Observatory (CARO) of ERATOSTHENES Centre of Excellence, located in Limassol (34.677° N, 33.0375° E, 2.8 m above sea level, a.s.l.) is part of the ACTRIS (Aerosols, Clouds, and Trace Gases Research Infrastructure) network. The ground-based station (GBS) station is Republic of Cyprus' National Facility (NF) for aerosol and cloud monitoring using active and passive remote sensing techniques.

CARO is equipped with a Polly^{XT} (POrtabLe Lidar sYstem) multi-wavelength, Dual-Field-of-View Polarization Raman Lidar [6]. It derives Elastic backscatter signals 355, 532 and 1064 nm and volume depolarization ratios at 355 and 532 nm.

The CUT-TEPAK Cimel sun/sky photometer AERONET site in Limassol is located near the Lidar, measuring simultaneously since 2020. The radiometer performs direct and diffuse sun and sky measurements of total optical depths and total scatter radiances across visible and NIR wavelengths, allowing the determination of key column optical and microphysical properties.

Figure 1. Map of Cyprus and Cyprus Atmospheric Remote Sensing Observatory location (CARO-LIM ACTRIS National Facility).

3. Methodology

A Saharan desert dust case was selected to evaluate the impact of volume depolarization ratio (VDR) in GRASP inversion code retrievals. The selection of the case was implemented according to the high attenuated backscatter on vertical profile evidence of the presence of a layer, and the high values of VDR observed by the Polly^{XT} Raman Lidar indicating non-spherical particles. The back-trajectory of the layer shows the source of the travelled air mass toward the study location. The analysis of the event is presented in the results section.

For the GRASP analysis, the multi-pixel approach used, more about this method can be found in literature [2, 5, 7].

Table 1 presents the input data from the Polly^{XT} Raman Lidar and the sun/sky photometer for both retrieval configurations, used in GRASP algorithm with and without VDR, for evaluation purposes.

Table 1. GRASP input data for the two configuration modes

Instrument	Configuration 1	Configuration 2
Polly^{XT} Polarization Raman Lidar	Elastic backscatter signals at 355, 532 and 1064 nm.	Elastic backscatter signals at 355,532 and 1064 nm, & Volume depolarization ratios at 355 and 532 nm.
Cimel Sun/sky photometer	Total optical depths, & Total scatter radiances at 440, 500, 675, 870, 1020 nm.	

GRASPs' vertical profiles of extinction and backscatter of aerosol layer are estimated with the following using GRASP inversion algorithm retrievals:

$$S_i(\lambda) = \frac{\sigma_i(\lambda, h)}{\beta_i(\lambda, h)}, \quad (1)$$

$$\sigma(\lambda, h) = \sum_{i=1}^{N} \tau_i(\lambda) v_i(h), \quad (2)$$

$$\beta(\lambda, h) = \sum_{i=1}^{N} \frac{\tau_i(\lambda) v_i(h)}{S_i(\lambda)}, \quad (3)$$

Where $\sigma(\lambda, h)$ is the aerosol extinction; $\beta(\lambda, h)$ is the aerosol backscatter; S_i is the spectral lidar ratio of the corresponding aerosol mode; N is the number of aerosol modes; $\tau_i(\lambda)$ is the Aerosol optical depth of the related mode; and $v_i(h)$ is the normalized aerosol vertical distribution profile of the corresponding mode.

AOD and SSA obtained straight forward from the output files of GRASP algorithm.

Vertical profiles of aerosol extinction and backscatter coefficients obtained for the two configuration modes 1 and 2 (no-depol and with depol) from GRASP outputs, were evaluated against measurements from Polly^{XT} Raman lidar and the column integrated AOD and SSA from AERONET level 1.5 products were used.

4. Results

The Polly^{XT} Lidar in Limassol on 25th of May 2025 captured a thick, intense temporally stable aerosol layer at height between 0.85 up to 4 km from the ground (see Figure 2). The time-height cross section of the (a) total attenuated backscatter coefficient at 1064 nm and (b) volume depolarization ratio at 532 nm are presented on Fig. 2. The increased attenuated backscatter on vertical profile evidence of the presence of a layer, while the high values of VDR indicate the presence of non-spherical aerosols. The time of the study of the selected layer is 05:00-07:00 UTC at altitude 0.85-4 km.

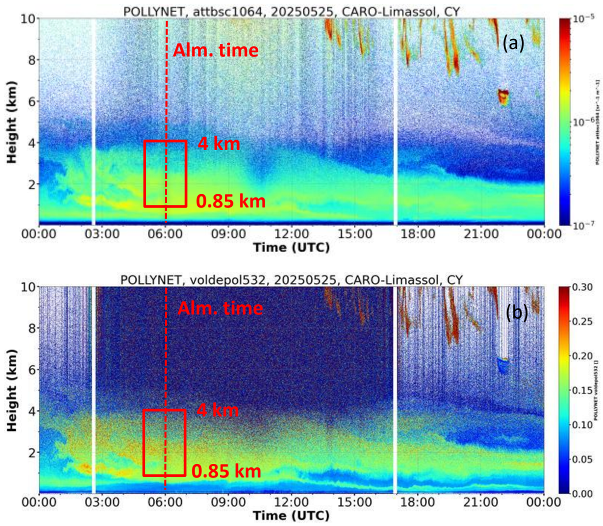

Figure 2. Quick-look plots from Polly^{XT} lidar (a) Attenuated backscatter at 1064 nm, (b) Volume linear depolarization ratio at 532 nm over Limassol, Cyprus, on 25 May 2025. The dashed line indicates almucantar studied time and red boarders the region of the studied aerosol layer.

According to HYSPLIT model, in Fig. 3 the 72-h backward trajectory arriving over Limassol, Cyprus (34.67 N°, 33.02 E°) at altitude 3 km at 20:00 UTC indicates that the airmass originated from Sahara Desert.

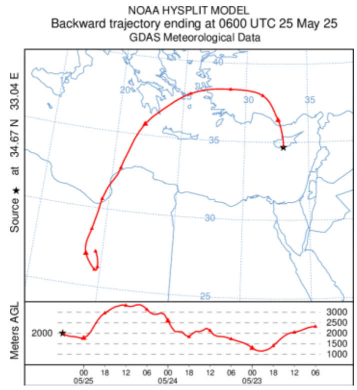

Figure 3. The 72h air mass backward trajectory at 2 km by HYSPLIT model on 25 May 2025 at 06:00 UTC. Source of air mass is Sahara Desert.

The vertical profiles of aerosol extinction and backscatter coefficients both at 532 nm retrieved from GRASP inversion algorithm for configuration 1, 2 and Klett signal from Polly^{XT} Lidar for 25 May 2025 at almucantar time 05:58:32 are presented in Fig. 4.

The daytime vertically resolved profiles of extinction and backscatter coefficients from Polly^{XT} Lidar are analyzed. The Verlauf tool is used for manual processing of Polly^{XT} lidar data for 05:00-07:00 UTC, and vertical smoothing 99 m. According to Lidar retrievals the studied layer (0.85-4 km) shows a mean particle linear depolarization ratio of 29% at 532 nm, pointing the dominance of coarse mode particles.

For extinction coefficient profile, small biases observed with better agreement of Lidar signal with retrieval of extinction profile from GRASP without the integration of VDR (configuration 1). This is due to the small layer observed at 4-5 km in the extinction profile from the retrieval of configuration mode 2 that doesn't match with the lidar profile (see Fig.4), possibly caused by the noise of VDR. The behavior of backscatter vertical profile showed good correlation of GRASP results and Lidar data using as input the VDR.

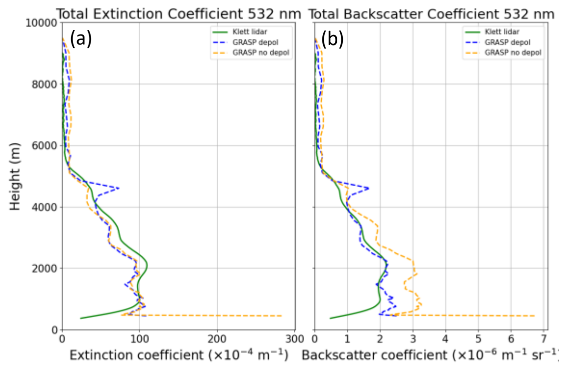

Figure 4. Comparison of the vertical profiles of (a) total extinction coefficient at 532nm, (b) total backscatter coefficient at 532 nm, on 25 May 2025 at almucantar time 05:58:32 UTC. Green solid line is the extinction/backscatter coefficient from Polly^{XT} lidar (Klett method), blue dash line from the retrievals of GRASP algorithm integrating VDR and orange dash line without VDR.

The comparison of AOD at 440 nm of GRASP retrievals with AERONET for configuration modes 1 and 2 are figured below. Overall, the GRASP retrievals show good agreement with AERONET code, both with and without the VDR (see Fig. 5).

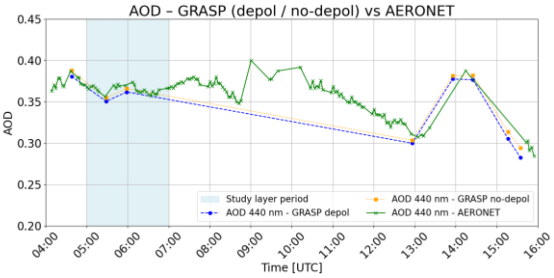

Figure 5. Comparison of the column integrated AOD at 440 nm on 25 May 2025. Green solid line is the AOD from AERONET lev. 1.5, blue dash line from the retrievals of GRASP algorithm integrating VDR and orange dash line without VDR.

5. Conclusions

The evaluation of GRASP retrievals for two configuration modes (with and without VDR) as input in the algorithm with Polly^{XT} Raman Lidar and radiometer of AERONET data are presented. A Saharan dust case introduced and analyzed. The vertical profile of extinction coefficient at 532 nm showed better correlation with lidar data observed for the case of no VDR. On the contrary, Backscatter coefficient vertical profile at 532 nm showed better correlation utilizing the VDR as an input to the algorithm.

On the other hand, AOD at 440 nm showed good agreement with AERONET for both configuration modes. More results will be presented at the conference.

6. Acknowledgements

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