APPLICATION OF REGULARIZATION ALGORITHM TO HSRL-2 OBSERVATIONS DURING ORACLES CAMPAIGN: COMPARISON OF RETRIEVED AND *IN SITU* PARTICLE SIZE DISTRIBUTIONS AND SINGLE SCATTERING ALBEDO

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ABSTRACT

Data obtained from HSRL-2 observations carried out on 20 September 2016 during the ORACLES campaign are publicly accessible. In our presentation we invert 3β+2α data into (1) particle size distributions with a regularization algorithm, and subsequently compute (2) single scattering albedo. We carry out a first comparison to the same particle characteristics measured with airborne *in-situ* instruments. We find good agreement of the data products. However, a more detailed study is needed as correction factors and sources of retrieval and measurement uncertainties need to be tested.

1. INTRODUCTION

Numerous approaches have been suggested for the retrieval of particle size distributions from multiwavelength lidar observations during the past 2 - 3 decades. Multiwavelength lidar based on a tripled Nd:YAG laser is capable to provide us with aerosol extinction coefficients (α) at wavelengths λ=355 and 532 nm and backscattering coefficients at 355, 532 and 1064 nm; we denote this data set as 3β+2α data. The retrieval of particle size distributions from 3β+2α data is a complex problem because the number of input optical data is limited and characterized by high measurement errors. Moreover, the range of possible variations of radii (r) and complex refractive indexes ($m=m_R-im_I$) is very wide. This makes the task of retrieving particle microphysical properties from 3β+2α measurements very challenging. Still, the results presented in [1] demonstrate that inversion with regularization is capable to provide estimates of microphysical parameters such as effective/mean radius (r_{eff}/r_{menan}), variance (σ), number (n), surface-area (s) and volume (v) concentration.

Validation of this approach can be carried out by comparing the retrieved particle size distributions with *in situ* measurements [2]. The data acquired in the framework of the campaign *Observations of Aerosols Above Clouds and Their Interactions* (ORACLES) is publicly accessible (https:// espoarchive.nasa.gov/ archive/ browse/ oracles). We took the opportunity of carrying out a comparison study based on the accessible data. The ORACLES data contain measured *in situ* particle size distributions together with time series of 3β+2α data measured with NASA Langley Research Center's high-spectral-resolution lidar (HSRL-2).

In this study we retrieve profiles of particle microphysical parameters and single scattering albedo from HSRL2 data with our regularization algorithm [1] and compare the inversion results to airborne *in situ* measurements.

2. METHODOLOGY

2.1 HSRL-2 Optical Data

During the ORACLES campaign HSRL-2 provided 3β+2α data with 300 m vertical resolution and 1 min (i.e. about 6 km at nominal aircraft speed) horizontal resolution (https:// espoarchive.nasa.gov/archive/browse/oracles/id8 /ER2) [3]. In this study 3β+2α data from the observations on 20 Sep 2016 between minutes 820 and 839 on that day, i.e. between 13:40 UTC and 13:59 UTC were averaged. During that time the aircraft travelled from −17.13° S to −19.30° S and from 8.24° W to 8.73° W (see table 1).

2.2 Regularization Algorithm

The HSRL-2 3β+2α measurements were inverted to the particle size distributions with a regularization algorithm [1]. Since 2004 the algorithm was updated with new options that allow for the processing of large volumes of data in an automated, unsupervised mode for a wide range of particle radii and complex refractive indices [4]:

$$r\in[0.03;10]\ \mu m;\ m_R\in[1.3;1.8];\quad m_I\in[0;\ 0.1] \quad (1)$$

2.3 *In situ* data

The particle microphysical and optical properties were measured via *in situ* sampling with an isokinetic, low-turbulence inlet mounted on the port side of the P-3B aircraft [3]. The samplings with 1 sec temporal resolution are available at https://espoarchive.nasa.gov/ archive/ browse/ oracles/P3/mrg1. In this study we analyze measurements taken between 5.2-5.5 km height on 20 Sep 2016 between 13:40 and 13:41 UTC. The P-3B aircraft travelled from −18.96° S to −19.02° S and from 9.78° W to 9.83° W (see table 1) during that time.

Table 1. HSRL-2 and in situ data measured in the framework of the ORACLES campaign

	3β+2α	*in situ*
Source	…/oracles/id8/ ER2	…/oracles/P3/ mrg1
File	HSRL2-Microphysics_ ER2_20160920_ R1.h5	mrg1_P3_ 20160920_R2 5.nc
Date	20 Sep 2016	20 Sep 2016
Latitude,°deg S	-17.13…-19.30	-18.96…-19.02
Longitude,°deg W	8.24…8.73	9.78…9.83
Height, m	959.1… 5680.9	5173…5514
Time, min	820…839	820…821

3. CASE STUDY

The 3β+2α profiles (20 Sep 2016) are shown in Fig. 1a-b. We obtained them by averaging the data (taken between 820 and 839 minutes since start of 20 Sep) into 20-minute intervals. The time intervals allow us to decrease the measurement uncertainties of lidar ratios and Ångström exponents (backscatter- and extinction-related) in the height range from 1.9 - 5.7 km (above sea level). Below 1.9 km height the data oscillate and cannot be used for the retrieval. For that reason, we only invert the 3β+2α profiles in the 1.9 - 5.7 km height range.

We also analyzed profiles of particle linear depolarization ratios measured by HSRL-2 at 355, 532 and 1064 nm. The depolarization ratios slightly decrease with height from 0.1 (at 1.3 km) to 0.02 (at 5.7 km). Thus, we used the spherical particle approximation in data inversion. 0.02 is well within the range of values (up to 0.05) in which the spherical particle model (Mie's light-scattering theory) can be used. Although 0.1 is already a bit too far outside that safe range we know from a few studies, e.g. [5, 6] that some particle parameters may be retrieved with acceptable accuracy. Thus, we also used these data in our study.

To retrieve the particle size distributions $dv(r)/dr$ the 3β+2α profiles from Fig. 1a-b were used as input in the regularization algorithm [1] The retrieval routine is carried out in an automated unsupervised fashion on the domains (1) without the use of any constraints on the solution space in consecutive order from the lowest height bin (l=1) at 1.9 km to the topmost one (l=13) at 5.7 km height above sea level. The analysis of the solution space at each height bin shows that the individual solutions are retrieved with a regularization parameter γ=0, i.e., regularization of the individual solutions is not needed. This result means that the quality of the HSRL-2 data used in this study is high. The final solution space of the particle size distribution is an average over those 100 individual solutions that are nearest (with regards to their own individual discrepancy values) to the minimum discrepancy, as shown in Fig. 2.

The particle size distributions retrieved below 4.4 km height have mean (effective) radii of approximately 0.1 μm for the fine and approximately 4 μm for the coarse mode. The only variation in the particle size distributions below 4.4 km is the particle concentration in the fine mode, which varies from 70 to 120 $\mu m^2 cm^{-3}$ (red and blue curves in Fig. 2). However, above 4.4 km the coarse mode decreases and cannot be identified anymore by the regularization algorithm at 5.7 km (solid black, gray and green curves).

We use the retrieved particle size distributions for our estimation of the particle microphysical parameters, i.e. effective/mean radius (r_{eff}/r_{mean}), variance (σ), number (n), surface-area (s) and volume (v) concentrations. The extensive microphysical parameters are proportional to the extinction coefficient α(355). Surface-area concentration varies from 80 to 500 $\mu m^2 cm^{-3}$, number concentration varies from 500 to 4600 cm^{-3}, and volume concentration varies from 5 and 55 $\mu m^3 cm^{-3}$; see Fig. 1e-f. The total effective radius, which correlates with the extinction-related Ångström exponent, varies from 0.17 to 0.4 μm.

The analysis of the retrieval results shows that s, v/r_{eff}, n ($r_{mean}^2+\sigma^2$) and α(355) are linearly correlated. Correlation coefficients are R>0.93. The correlation coefficient for effective radius versus the extinction-related Ångström exponent is R>0.8. The regression coefficients that describe the linear correlation relationships (not shown) agree with those that were used in [7]. This fact again may support our assumption regarding the high quality of the HSRL-2 3β+2α data in the 1.9-5.7 km height range.

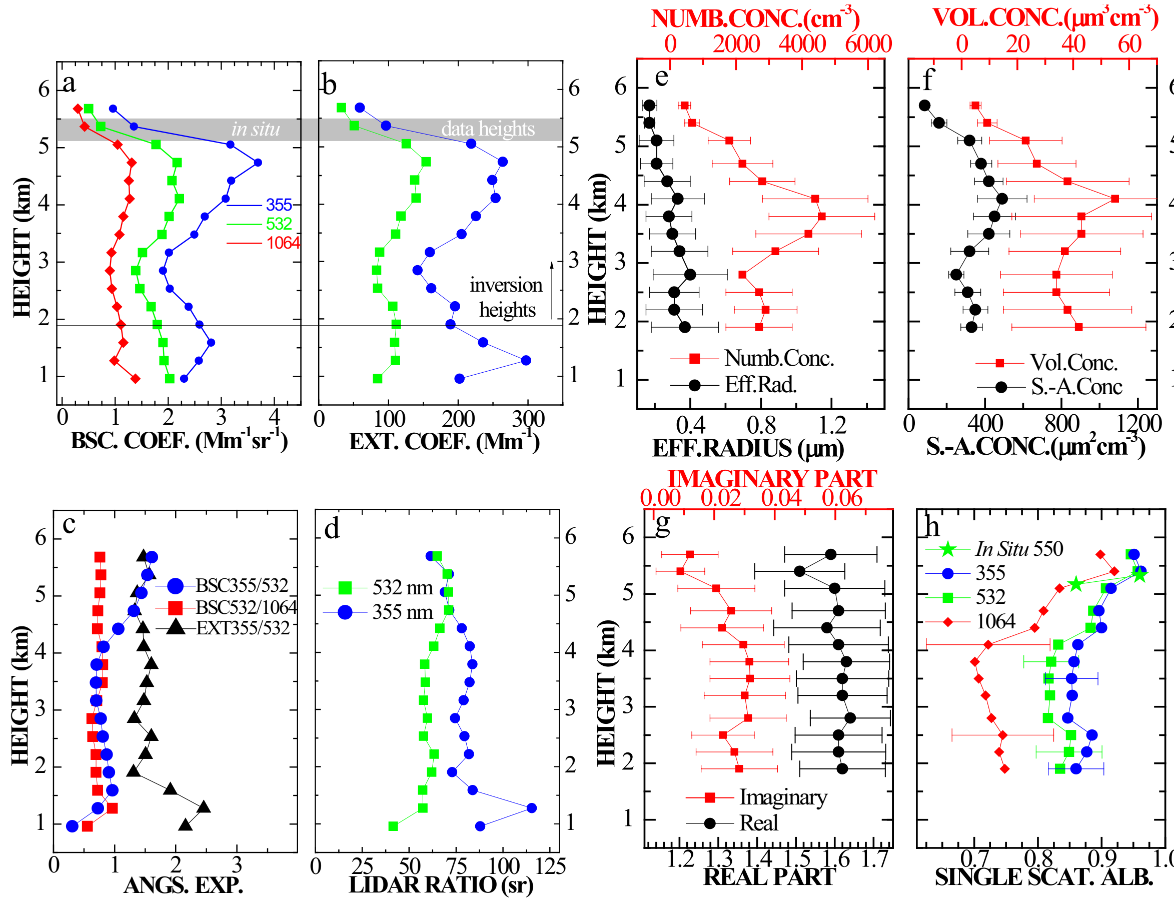

Fig.1. Profiles of the backscattering (a) and extinction (b) coefficients measured with HSRL-2 at 355, 532, and 1064 nm together with the backscatter- and extinction-related Ångström exponents (c) and the lidar ratios (d). The backscattering and extinction profiles describe 20-minute averages of data taken between 820 (equivalent to 13:40 UTC*) and 839 minutes (equivalent to 13:59* UTC*) since start of 20 Sep 2016. Profiles of particle effective radius (e, circles), number (e, squares), surface-area (f, circles) and volume (f, squares) concentrations, real (g, circles) and imaginary (g, squares) parts of the complex refractive index, and single scattering albedo(h) were retrieved with the regularization algorithm from the profiles of the 3β+2α data, see Fig.* 1*a-b. The green stars correspond to in situ measurements at 550 nm.*

The retrieval algorithm also allows us to estimate the complex refractive index from the optical data, see Fig. 1g. The real part does not depend on height and is approximately 1.6; the exception is the height bin at 5.4 km. The imaginary part is approximately 0.03 and does not change significantly from this value below 4.4 km height above sea level. It decreases to 0.01 above 4.4 km height above sea level. This decrease of the imaginary part may (at least in part) explains the increase of the backscatter-related Ångström exponent (at 355/532 nm) with height; see blue curve in Fig. 1c. This behavior also explains the increase of particle single scattering albedo at 355 and 532 nm from 0.90 to 0.95 above 4.4 km height (see Fig. 1h).

Finally, we compare the retrieval results with *in situ* data. We averaged into size bins the particle concentrations $n(r)$ measured *in situ* and retrieved from the HSRL-2 observations. The averaging time is approximately 1 minute for the P-3B aircraft data. We note that the aircraft travelled above 5.5 km height after 13:41 UTC during the time we use for this comparison. We note that the lidar data degraded above 5 km height above sea level during that time. Data are not available above 5.7 km height above sea level after minute 822 on that day. Thus, we need to take the comparison with some caution. We converted the *in-situ* value of $n(r)$ ["# particles per cm^3 per log10"] into units of a volume particle size distribution d$v(r)$/dr [μm^{2}cm^{-3}]. For that purpose we used the equation

$$dv(r_i)/dr = \frac{4}{3ln(10)lg\frac{r_{i+1}}{r_i}}\pi r_i^3 n(r_i)$$

i=1,2,… (2)

The parameter r_i denotes the radius bins that were used for the *in-situ* measurements of the particle size distributions (see black dotted curve in Fig. 2). Unfortunately, the *in-situ* measurements of the particle size distributions covered only the particle radius range r<0.5 µm. Thus, we cannot compare the regularization results and the *in-situ* measurements for particles above 0.5 µm. It also remains unclear if particle loss effects caused by the inlet system were significant and how they were corrected for.

Finally, we note that relative humidity measured *in situ* at 13:40 UTC had decreased from 60% to 10% (not shown). This low value makes it unnecessary to carry out a humidity correction of the radius of the observed particles.

Fig. 2 shows that the particle size distributions retrieved with the regularization algorithm at 5.1 km (black solid line) and at 5.4 km (gray line) height above sea surface. The *in-situ* data show the average value between 5.2 and 5.5 km height (black dot). The data cover the radius range from 0.03 to 0.5 µm. We find reasonable agreement, i.e. position (radius bin) of the maximum value of volume particle size distributions in these heights. The maximum value measured *in-situ* is between respective values retrieved with regularization algorithm at 5.1 and 5.4 km. Single scattering albedo retrieved at 532 nm and measured *in situ* at 550 nm coincide if we take account of the involved uncertainties. We find a value of ~0.96 at 5.4 km height in both approaches.

4. CONCLUSION

We inverted 3β+2α data taken with HSRL-2 on 20 Sep 2016 during the ORACLES campaign. We identified two aerosol layers and analyzed two height bins for our study. The lower aerosol layer, below 4.4 km height above sea level, is characterized by a bimodal particle size distribution. In the upper aerosol layer above 4.4 km height the coarse mode disappears. Simultaneously, the imaginary part of the complex refractive index decreases to 0.01 in the upper aerosol layer. A first comparison of the results obtained with the regularization algorithm (between 5.1-5.4 km height) and measured with *in-situ* instruments (between 5.2-5.5 km height) agree reasonably well.

A future, more detailed study of the ORACLES data needs to include a sensitivity study on the uncertainties of the optical input data and uncertainties of the data products we inferred from the regularization algorithm and measured with the *in-situ* instruments.

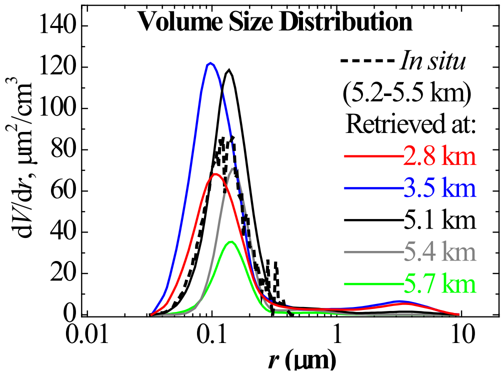

Fig. 2. Particle size distributions measured in situ (see dotted black curve and details in Table 1) and retrieved with the regularization algorithm (solid curves) from the 3β+2α data (see Fig. 1) at different height levels (see legend).

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