POTENTIAL RETRIEVAL OF AEROSOL MICROPHYSICS FROM MULTISTATIC SPACE-BORNE LIDAR

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ABSTRACT

HSRL lidars are being considered for deployment to space to retrieve aerosol microphysics. The literature is mostly focused on the monostatic configuration; but, in this paper, we explore whether additional information for the retrieval of microphysics can be obtained by adding a second detector in a bistatic configuration. The information gained from the additional measurements can under certain conditions reduce the ill-posed nature of aerosol microphysics retrieval and reducing the uncertainty in the retrievals.

1 INTRODUCTION

Aerosol microphysics is an important part of characterizing the atmosphere and better understanding the effects of aerosols on earth's energy balance. Conventional multispectral backscatter lidars simply do not have the information content needed. To address this limitation, a novel space-born multistatic lidar system has been proposed in the literature [1] to better characterize the vertical distribution of aerosol microphysics on a global scale. The proposed multistatic configuration allows for the retrieval of more intensive aerosol properties because it measures information about the scattering matrix elements at angles other than those obtained from pure backscattering (180°). While the sensitivity of the difference in the scattering matrix elements from the off-nadir and on-nadir angles was demonstrated in previous works [1], we are not aware of any effort to assess the improvement in the potential retrieval of realistic aerosol size distributions. In this paper, we explore the potential to improve the retrieval of the size distribution parameters and the refractive indices through the addition of the off-nadir measurements.

We compare the bistatic case to the traditional monostatic 3β + 2α High Spectral Resolution Lidar (HSRL) measurement configuration, being considered for deployment to space by NASA [2]. Many ground-based studies [2] have indicated that this is the minimum measurement dataset needed to retrieve information about the aerosol microphysics and an air-borne monostatic 3β + 2α HSRL system has been deployed by NASA Langley in preparation for a possible space-born mission. The ground-based studies have also concluded that HSRL must be used because of its ability to separate measurements of extinction and backscatter at the physical layer without an estimation of the lidar ratio (The variability of the lidar ratio causes a large increase in the uncertainty if it is estimated and not measured). In the multistatic configuration, the concept of β is extended to the multi-angular domain and it reflects the signal scattered back to the sensor at scattering angle θ (rather than simply backscattering at 180°). Specifically, we define this quantity as

$$\beta_{dbs}(\theta) = \frac{\omega_0 \beta_e F(\theta)}{4\pi} \quad (1)$$

where $F(\theta)$ is an element of the scattering matrix. As a result, in the bistatic configuration, there are 6 measurements of β_{dbs} per polarization in the 3β + 2α configuration (3 at each angle).

The concept of backscattering can be expanded to the polarization domain by considering the entire scattering matrix. For example, in the case of a lidar emitting circularly polarized radiation, the measured Stokes vector can be related to the atmospheric aerosol distribution as

$$\begin{bmatrix} I(z) \\ Q(z) \\ U(z) \\ V(z) \end{bmatrix} = \frac{1}{4\pi} \begin{bmatrix} C_I(z)\beta_s F_{11}(\theta) \\ C_Q(z)\beta_s F_{12}(\theta) \\ C_U(z)\beta_s F_{34}(\theta) \\ C_V(z)\beta_s F_{44}(\theta) \end{bmatrix} e^{(sec\theta-1)\int_0^r \beta_e(z')dz'} \quad (2)$$

The inclusion of an off-nadir angle in the bistatic configuration allows for access to the polarization measurements for retrieval of the microphysics of spherically symmetric particles. At 180°, information about spherically symmetric particles is contained in F_{11} and the other polarization channels can only be used to determine the particle's nonsphericity. In contrast, at off-nadir angles, the other elements of the scattering matrix also contain information about spherically symmetric particles and this information can be exploited to improve the retrievals of the microphysics [1].

For a particle size distribution, the directional backscatter coefficient has a simple expansion as

$$\beta_{dbs}(\theta) = \frac{1}{4\pi}\int_{-\infty}^{\infty} \frac{dV(r)}{dlnr}\frac{3}{4}\pi r^{-3}\beta_s(r)F(\theta,r)dlnr \quad (3)$$

From this expression, we can define the particle size distribution backscatter weighting function as

$$W_{dbs}(r,\eta) = \frac{3}{4}\pi r^{-3}\beta_s(r)P(\theta,r) \quad (4)$$

For every refractive index and axial ratio distribution, the weighting function in equation 4 is known from either Mie theory (if the axial ratio distribution states that the particles are spherical) or the T-matrix method [3]. Because of the weighting functions are known, the inversion of the size distribution from measurements of β_{dbs} takes the form of the solution of the Fredholm integral problem in equation 5.

$$\beta_{dbs}(\theta) = \frac{1}{4\pi}\int_{-\infty}^{\infty} \frac{dV(r)}{dlnr} W_{dbs}(r,\theta)dlnr \quad (5)$$

Measurements of the extinction coefficient are also related to the size distribution through a similar Fredholm integral problem listed in equations 6 and 7.

$$W_e(r,\eta) = \frac{3}{4}\pi r^{-3}\beta_e(r) \quad (6)$$

$$\beta_e = \frac{1}{4\pi}\int_{-\infty}^{\infty} \frac{dV(r)}{dlnr} W_e(r)dlnr \quad (7)$$

It has been extensively documented [4,5] that the problem of inverting equations 5 and 7 to retrieve the size distribution and refractive index is ill-posed, even when the number of unknown microphysics parameters is greater than the number of measurements. This is because, especially when the refractive index is unknown and the best weighting function has to be selected, the inversion is not unique. To address the ill-posedness, the retrieval algorithm needs regularization to select only those solutions that are likely to occur in nature. In other words, some information about the typical distributions atmospheric aerosol needs to be incorporated into the algorithm.

2 METHODOLOGY

This paper seeks to explore the benefits of adding a second receiver at an off-nadir angle for a space born 3β + 2α HRSL system. To do so, we simulated measurements by using aerosol microphysics retrievals from AERONET [6]. Specifically, we use the six bimodal lognormal size distribution parameters and the complex refractive indices retrieved by AERONET to simulate the measurements. We used 10,000 randomly selected AERONET retrievals to generate a database of 10,000 sets of simulated multistatic lidar measurements. These AERONET retrievals and simulated measurements form our characterization of typical atmospheres that can be used by a retrieval algorithm to regularize the ill-posed problem of microphysics inversion from lidar data. We consider both monostatic 3β + 2α measurement set and the bistatic 3β + 2α measurement set. The monostatic measurement set consists of measurements of the extinction coefficient (α) at 355 and 532 nm and measurements of the backscatter coefficient (β) at 355, 532, and 1064 nm. The bistatic measurement set we consider augments the monostatic measurements with six measurements of β_{dbs} at 170° (same three wavelengths and two polarization bands sensitive to F_{11} and F_{12}, respectively). We chose 170° to perform the analysis because the error caused by horizontal aerosol inhomogeneity is minimal at this angle [1].

We perform a statistical analysis to determine the anticipated error in microphysics retrieval for the monostatic and bistatic configuration. We add Gaussian error to each of the measurements in the retrieval subset with a standard deviation/measurement ratio of 0.1 for β measurements and 0.15 for α measurements (which corresponds to 10% and 15% error, respectively). Then, for every retrieval measurement, we computed a weight for every database measurement in the whole database based on the joint Gaussian PDF, the standard deviation/measurement ratios above, and an assumption that the errors in the individual measurements are uncorrelated. These weights allow us to get an estimated retrieval for each measurement in the retrieval subset by taking the weighted average of the database aerosol distribution parameters (bimodal lognormal size distribution parameters and refractive indices). Then, across all the retrievals in the retrieval subset, we find the mean retrieval, mean retrieval error, and the standard deviation of the retrieval error for all the aerosol parameters. The standard deviation of the retrieval error and the mean retrieval error as a percentage of the mean retrieval are shown in the results. In this simlation study, we focus only on non absorning aerosols and limit the imaginary ref index < .01. This was needed since without the constraint, significant errors in this method can result. However, if we make use of simultaneous measurements from OMI and filter out high Absorbing Indices, the results of this study can be used to extract useful vertical PSD information.

3 RESULTS

The results of the statistical analysis we described in the methodology section are presented in Tables 1 and 2.

First, we note that the low mean retrieval errors in Table 2 (as compared to the standard deviations in Table 1) indicates that the bias of our retrievals is low and the error is mostly driven by random retrieval scatter, which is seen in the standard deviation. The standard deviations in Table 1 clearly demonstrate the information gain for retrieval of aerosol microphysics by adding a detector at 170° in that the retrieval error standard deviations are reduced by more than 50%. Specifically, the average error in the retrieval of all the aerosol parameters is 19.5% in monostatic case and 7.86% in the bistatic case.

Table 1: Standard deviation of aerosol parameters error as percentage of mean retrieval

	Standard deviation as percentage of mean retrieval (Monostatic 180°)	Standard deviation as percentage of mean retrieval (Bistatic 170° and 180°)
Fine Mode Volume Concentration	29.06%	14.07%
Fine Mode Volume Median Radius	19.16%	5.47%
Fine Mode Lognormal Std. Dev	14.01%	5.93%
Coarse Mode Volume Concentration	60.26%	19.81%
Coarse Mode Volume Median Radius	17.08%	8.73%
Coarse Mode Lognormal Std. Dev	10.22%	5.81%
Refractive Index Real Part 1022 nm	3.28%	1.56%
Refractive Index Imaginary Part 1022 nm	2.98%	1.55%

CONCLUSIONS

In this paper, we explored the ability of a space-born 3β + 2α HRSL multistatic lidar to perform retrievals of aerosol microphysics from space. We found that the bistatic configuration does work to reduce the ill-posedness of the inverse problem as it significantly reduces the percentage error in retrieval space compared to the monostatic configuration when the complex refractive index is sufficiently low. The non-uniqueness of the solution is the primary difficulty in the retrieval of aerosol microphysics from lidar

	Mean retrieval error as percentage of mean retrieval (Monostatic 180°)	Mean retrieval error as percentage of mean retrieval (Bistatic 170° and 180°)
Fine Mode Volume Concentration	3.44%	2.33%
Fine Mode Volume Median Radius	0.68%	0.37%
Fine Mode Lognormal Std. Dev	0.71%	0.1%
Coarse Mode Volume Concentration	0.14%	0.13%
Coarse Mode Volume Median Radius	0.75%	0.25%
Coarse Mode Lognormal Std. Dev	0.3%	0.001%

Table 2: Mean retrieval error of aerosol parameters as percentage of mean retrieval

measurements and this reduction in the ambiguity is of great aid to inversion algorithms. Further climatological constraints on the aerosol microphysics parameters as well as Ssuitable filtering of absobing cases using OMI should be incorporated in a future retrieval algorithm for the multistatic configuration that would further increase the accuracy by reducing the size of space of typical atmospheric aerosol parameters.

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