P6.2 THE RETRIEVAL OF THE HORIZONTAL PROFILE OF THE AEROSOL PARTICLE SIZE DISTRIBUTION FROM LIDAR DATA

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1. INTRODUCTION

The interpretation of lidar data is based on certain assumptions regarding the properties of the scattering medium (see, for example, Klett (1985); Weinman (1988); Young et al. (1993); Porter et al. (2000)). Two aerosol optical characteristics can be obtained by inverting the measured lidar signal: the aerosol spectral extinction σ and backscattering β, with the extinction often being the sole independent quantity. Considering that the lidar performs only at a few points of the spectrum, the resulting data set is hardly enough for a successful retrieval of the aerosol microphysical structure by traditional methods. The method of mean ordinates (Shifrin and Zolotov, 2000) was developed for inverting scarce and/or incomplete optical information of this kind. It makes possible, under certain conditions, the retrieval of the aerosol particle size distribution (APSD) from lidar data at two and even one wavelength. When doing this, the retrieval accuracy is comparable with that of direct APSD measurements. The method also allows the determination of the aerosol component presenting some problem for direct observations, namely, the large-particle fraction of APSD ($r \geq 5$ μm). The method of mean ordinates overcomes some shortcomings peculiar to the so-called look up tables, such as a limited set of initial models and the definition of the solution as the model yielding the closest optical characteristics to the experiment. In contrast, the method of mean ordinates is based on a wide variation of aerosol parameters, which results in a more accurate selection of acceptable solutions. The most probable solution is defined as the acceptable solution that is found to be the closest to the mean over the whole ensemble of acceptable solutions. In this way an error is avoided connected with a possible low accuracy of the experiment.

2. COMPARISON OF THE INVERSION RESULTS WITH EXPERIMENTAL DATA

The method of mean ordinates was tested in many numerical experiments for different aerosols under different conditions. The error of inverting the aerosol extinction into APSD was found to be 15-30%. The experimental data of the Shoreline Environmental Aerosol Studies (SEAS) 2000 were used for the tests by real data. The inversion was performed with lidar data obtained by the group of Dr. Sharma. Of the two lidar channels employed at SEAS (0.532 and 1.064 μm), only the first one turned out to be suitable for our purposes, because of a lower accuracy and higher noise at 1.064 μm (Shifrin and Zolotov, 2002). The inversion results were compared with the direct APSD measurements performed at 5 and 15 m above the ground by the investigators of the group of Dr. Clarke. As it is shown in (Clarke et al, 2002), the aerosol extinction calculated from the measured APSD at the shoreline somewhere between 5 and 15 m above the ground, corresponds with the lidar-derived extinction at, roughly, 300 m offshore. For this reason, the APSD by inversion at 300 m from the lidar site was compared with the average between the measured APSD at the 5 and 15 m levels.

An important part of the inversion algorithm is the construction of a set of aerosol models among which the solution would be chosen (so-called “initial“ set of models). A priori information on the specifics of the sought-for aerosol is used for constructing the initial set. This helps to determine as close as possible the character of the particle size distribution and to preset the limits of its parameter variations. Next, the parameter intervals are quantized, and the quantized parameters are combined in all possible ways in order to form the initial set of models. In this work we constructed two initial sets. The first set was based on aerosol data available in literature regarding oceanic aerosol in the lower part of the marine atmospheric boundary layer (LP MABL) (Shettle and Fenn, 1979, d'Almeida et al, 1991). The second one used averaged direct SEAS observations over APSD. A four-component aerosol model was constructed. Two lognormal distributions represented two small-particle aerosol fractions; the third distribution was for medium-sized particles. The fourth distribution was based on the observations by De Leeuw (1986) over large particles.

Fig. 1 presents the comparison of the inversion results for both aerosol parameter sets with the direct SEAS data for APSD. It is seen that the main difference between the APSD by inversion for the first set and the experimental curves at the two levels is that the curve by inversion is smoother than the other two. In the experimental curves, the modes of the small- and medium-sized particle components are clearly defined, whereas in the curve by inversion, they are

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imperceptible. The small-particle mode of the curve by inversion interpolates the first two modes of the experimental curves. This is no surprise, since the APSD by inversion was obtained from a single value of the aerosol extinction.

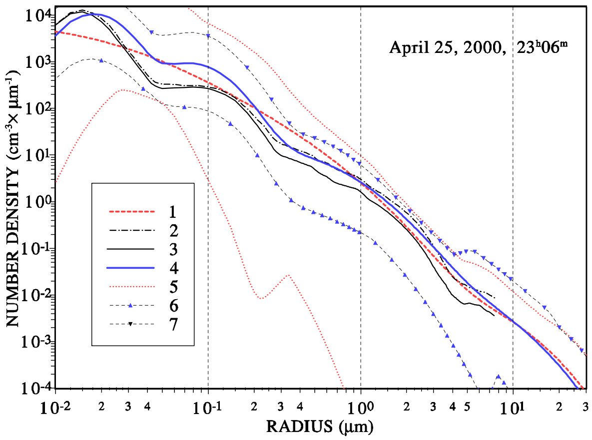

Fig.1. Inversion results by the method of mean ordinates for 23h06m, April 25, 2000.
1, inversion with the use of the first set of initial parameters; 2, measured APSD at the 5 m level; 3, measured APSD at the 15 m level; 4, inversion with the use of the second set of initial parameters; 5, curves of minimal and maximum ordinates of the ensemble of acceptable solutions for the first set of initial parameters; 6,7, curves of minimal and maximum ordinates of the ensemble of acceptable solutions for the second set of initial parameters.

The inversion results for the second parameter set show a noticeable improvement compared to the first set. It is seen that the calculated APSD is as much elaborated as the experimental one. The third component is close to the experimental third component in terms of the mode position, width, and height. The positions of the first and second modes are reproduced quite satisfactorily, although the heights of the distributions differ, sometimes significantly so. This latter fact is, however, of no great importance, because the contribution of the first two components into the total aerosol extinction is practically of the same order as its error.

Unfortunately, we have no SEAS data for particle radii larger than 7.5 µm. Because of this, the actual presence of large particles (the third component in the first set and the fourth component in the second set), as well as their concentration are hypothetical to a degree. This component, if it does present, is generated by surf and lives for a very short time (De Leeuw, 1986). Nevertheless it can create a noticeable optical effect near the sea surface. From our inversion results, the mode of this component falls on a particle radius interval of 5.4-8.6 µm. Its particle concentration varies from moment to moment between 0.02 and 0.06 cm^{-3}.

As it is clearly seen from Fig. 1, the area of acceptable solutions (i.e. solutions satisfying the optical data) for the second set of initial parameters is noticeably narrower than for the first set. We mean the area between the curves 5 for the first set, and the area between curves 6 and 7 for the second set. The explanation for this is that for the second set, real experimental data were used instead of parameters from the general theory.

3. INVERSION OF AEROSOL EXTINCTION INTO THE PROFILE OF NUMBER DENSITY.

A great body of APSD data was obtained at the ocean shore by direct observations during SEAS. It was expedient to use all this vast material for constructing an initial set of models in order to retrieve the aerosol profile over the sea surface from lidar data. Fig. 2 shows the area of all measured APSD at 5 and 15 m above the ground.

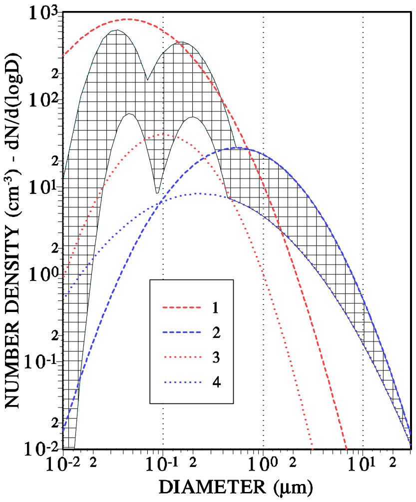

Fig.2. The determination of the initial set of models. The crosshatched area represents all APSD measured during SEAS at the both levels.
1,3, the upper and lower boundary model of the small-sized aerosol fraction; 2,4, the upper and lower boundary model of the medium-sized aerosol fraction.

We constructed lognormal distributions following the envelopes of this area. When doing so, we approximated two small-particle components by one distribution (because of their indistinguishable optical effects). As a result, the initial APSD set consisted of three-component lognormal models. The parameter sets for the small-particle and medium-particle fractions were constructed with the use of the curves 1,3, and 2,4, while the large-particle component was based on the observations over large aerosol particles in LP MABL (de Leeuw, 1986).

The corrected in this way parameter set was used for inverting the lidar-derived aerosol extinction. Ten profiles of the aerosol extinction obtained by the SEAS lidar group were utilized for this purpose. The profiles were related to five time intervals of 10-15 minutes. It is seen from Fig.3a that aerosol extinction profiles for different moments differ significantly. The authors of the σ profiles did not report the instrumental error and the error of inverting the backscattered lidar signal into the aerosol extinction. In order to estimate these errors, we smoothed the aerosol extinction by the running mean, using different distances: 25, 50, 100, and 200m. The results are shown on Fig.3b.

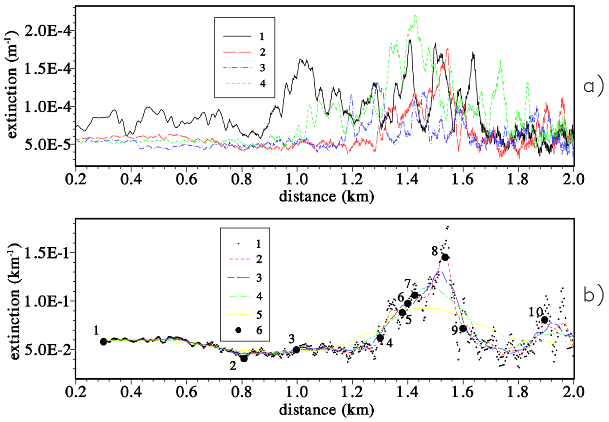

Fig.3. a) Horizontal profiles of the lidar-derived aerosol extinction σ at 0.532 μm for April 25, 2000 from 23h06m to 23h17m.

b) Juxtaposition of the lidar-derived aerosol extinction σ and their profiles smoothed over different distances.

1, experimental σ; 2,3,4, and 5, profiles smoothed over 25, 50, 100, and 200 m respectively; 6, points chosen for the inversion.

It is seen that long smoothing intervals cause considerable distortions around individual peaks. For this reason, the points chosen for the consequent inversion were taken from the curve smoothed over a distance of 25 m. For the data error, which is a necessary parameter of the inversion algorithm, was taken the standard deviation of the smoothed curve from the experimental one. Its magnitude varied from 3% nearer to the shore (up to 800 m) to 5% farther seaward (up to 2000 m). The points chosen for the inversion are numbered on Fig. 3b. Generally, 10-15 points were chosen from each profile in such a way that magnitudes of σ differed noticeably from each other.

The results of the inversion in these points are shown on Fig. 4. The general run of the curves for all points looks quite similar at this scale. The difference between them is not in the shape, but rather in the position of each curve on the graph.

Fig. 5 shows profiles of the aerosol number density along the lidar beam for 23h10m, April 25, 2000. Red circles on Fig. 5a represent the total number density N (cm^{-3}) obtained at each point by inversion independently from other points. On account of the inversion being performed with data for only one lidar channel, we checked the results with another method. Taking N obtained independently at some point, we determined N at other points by using the ratio of the aerosol extinctions between the points. After exhausting all 10 points, we got 10 estimates of N for every point. The black circles on Fig. 5a represent the calculated number density at each point; blue circles show the mean N at each point. Error bars represent standard deviations.

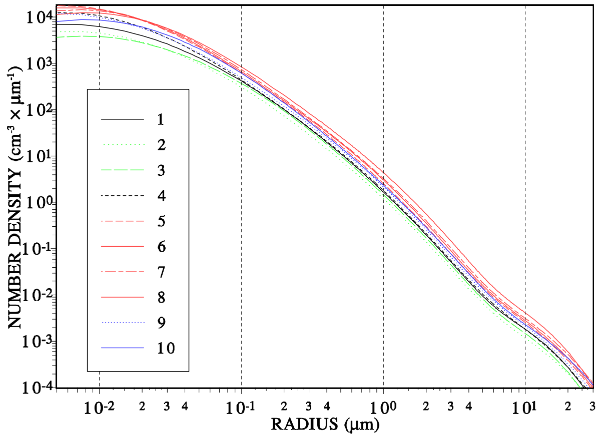

Fig.4. The APSDs by inversion (23h10m of April 25, 2000). 1-10, APSDs by inversion for the numbered points;

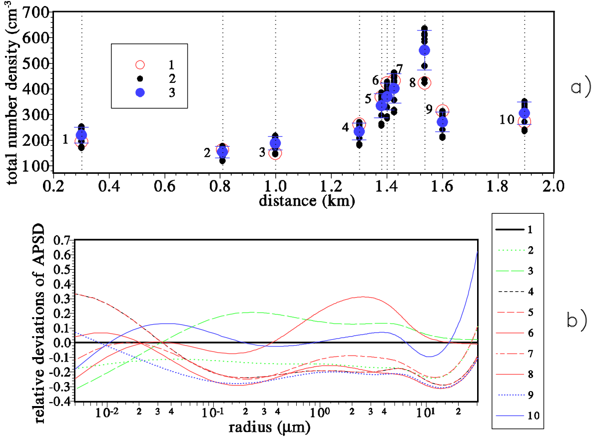

Fig.5 a) The aerosol density number N in LP MABL along the lidar beam on April 25, 2000, 23h10m. 1, N obtained by inversion independently at each point; 2, N estimated from the ration of aerosol extinctions at different points; 3, N averaged over the estimates by the second method.

b) Relative APSD deviations; 1 – 10, numbering of the points chosen for the inversion.

It should be noted that although the absolute values of standard deviation are different at different points, the relative standard deviations is constant. This is explained by the method of estimation, because the relative deviation of N was determined by the deviation of the ratio N_i/σ_i, where i = 1,2, …10 are the points on the σ profile.

It is seen from Fig. 5a that the independent estimates of N differ from the estimates by the ratio of σ at different points by no more than the standard deviation. The only exception is point 8 at the maximum of σ on the profile. However, even there, the difference does not exceed two standard deviations. It may be concluded from Fig. 5a that horizontal variations of the aerosol extinction over the sea during SEAS were determined primarily by variations of the aerosol number density in LP MABL. Variations of APSD shape played a secondary role.

Fig. 5b shows deviations of the normalized APSD (ASPD reduced to one particle) in relation to the APSD at the first point on the profile. It is seen that the reduced APSD differ from point 1 by no more than 30%, except for the largest and the smallest particles. This is well within the APSD error, be it obtained by inversion or by direct observations.

It should be noted that the curve for point 8 at Fig.5b shows a bulge at the optically active interval (0.5-5 μm), which corresponds with a greater deviation of N. It is likely that the shape of APSD at this point differs most from the average over the lidar signal path. This assumption is corroborated by the fact that point 8 is situated at the site of a spray.

4. CONCLUSIONS

1. The method of mean ordinates for determining the aerosol microphysical characteristics in LP MABL from the backscattered lidar signal was checked against direct observations over APSD during SEAS. The tests confirmed the efficiency of the method, even when dealing with lidar data for only one wavelength.
2. The horizontal profile of the aerosol number density was retrieved from the lidar-derived aerosol extinction. It was proven that the method of mean ordinates makes it possible to retrieve the profile of aerosol number density with a reasonable accuracy by using lidar data at only one channel.

REFERENCES

Clarke A., V. Kapustin, S. Howell, K. Moore, B. Lienert, K. Shifrin, and I. Zolotov, 2002: Sea-salt size distributions from breaking waves: implications for marine aerosol production and optical extinction measurements during SEAS (Submitted to *J. Atmos. Oce. Tech*.).

d'Almeida,G., Koepke, P., and Shettle, E., 1991: Atmospheric Aerosols. Deepak Publ.

De Leeuw G., 1986: Size distributions of giant aerosol particles close above sea level. *J. Aerosol Sci.,* **1**7, 293-296.

Klett, J.D., 1985: Lidar inversion with variable backscatter/extinction ratios. *Appl.Opt.*, **24**,1638-1643.

Porter J.N., B. Lienart, and S.K. Sharma, 2000: Using horizontal and slant lidar measurements to obtain calibrated aerosol scattering coefficients from a coastal lidar in Hawaii. *J. Atmos. Oceanic Technol.,* **17,** 1445-1454.

Shettle, E.P., Fenn, R.W., 1979. Models for Aerosols in the Lower Atmosphere and the Effects of Humidity on the Optical Properties. AFGL-TR79-0214 (US Air Force Geophysics Laboratory, Hanscomb Airforce), pp 94.

Shifrin, K.S., and I.G. Zolotov, 2000: The determination of the microphysical characteristics of aerosols in the lower part of the marine atmospheric boundary layer from the structure of the backscattered lidar signal. FY 99 Annual Report, Office of Naval Research – Ocean, Atmosphere, and Space.

Shifrin, K.S., and I.G. Zolotov, 2002: The use of direct observations over the aerosol particle size distribution for inverting lidar data (Submitted to *J. Atmos. Oce. Tech*.).

Weinman, J.A., 1988: Derivation of atmospheric extinction profiles and wind speed over the ocean from a satellite-borne lidar. *Appl.Opt.*, **27**, 3994-4001.

Young, S.A., D.R. Cutten, M.J. Lynch, and J.E. Davis, 1993: Lidar-derived variations of the backscatter-to-extinction ratio in southern hemisphere coastal marine aerosols. *Atmos. Environ.*, **27A**, 1541-1551.