Retrieval of atmospheric aerosol characteristics from spectral measurements of transparency and small-angle scattering

M.A. Sviridenkov

A.M. Obukhov Institute of Atmospheric Physics, Russian Academy of Sciences, Moscow

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The possibility of applying the measurement data on spectral transparency of the atmosphere in retrieving single scattering characteristics from observations of solar aureole is discussed. A simple iteration algorithm for such retrieval is suggested. It is shown that at a moderate atmospheric turbidity, inverting separately the phase functions of the aureole brightness and spectral transparency enables one to obtain the aerosol size distribution without subtracting the background due to multiply scattered light.

Introduction

The main difficulties in interpreting the data on brightness of the clear sky are related to the necessity of selecting a scattering phase function to fit the observed brightness. In particular, it is necessary to have data in as wide range of scattering angles as possible that cannot be met at large zenith angles of the Sun. Cloud cover of the sky often makes the observations difficult. Spatial inhomogeneity of aerosol can affect the accuracy of measurements at low Sun. Measurements in the small-angle range (2–10°) are more simple for instrumental realization, and are appreciably free of the above-noted drawbacks. However, to determine the single scattering characteristics, it is necessary to attract *a priori* data on the behavior of scattering phase function out of the measurement range.

At present there are several approaches to solving this problem. In using the small-angle approximation for solving the transfer equation (see, for example, Ref. 1) the contribution of radiation scattered at large angles and reflected from the underlying surface is neglected. Authors of Ref. 2 suggest an analytical representation of the multiple scattering phase function with the parameters depending on the turbidity factor, zenith angle of the Sun, and wavelength. Extension of the scattering phase function to the range out of scattering angles where the measurements have been done[3] is also used.

The aureole brightness is significantly caused by scattering on coarse aerosol particles. Joint inversion of the data of aureole measurements and the spectral dependence of the aerosol optical thickness (AOT) makes it possible to extend the range of the size spectrum retrieved. In this paper we consider the possibility of making use of the data on spectral transparency measured in parallel for interpretation of the small-angle measurements. The model particle size distributions close to real ones obtained from the data of measurements in different geographical regions were used in the analysis. The brightness field of incoming radiation was calculated by the Monte Carlo method using the codes written by Dr. T.B. Zhuravleva.

1. Retrieval of the single scattering phase function

Aerosol optical thickness in the visible range is mainly formed due to the light scattering by submicron aerosol fraction (except for the extreme situations similar to the dust haze). The same fraction causes scattering in a wide angular range except for the angles close to the backward and forward directions. Hence, one can expect that microphysical extrapolation of AOT to the scattering phase function (solution of the inverse problem and subsequent calculation of angular characteristics for the obtained particle distribution) will allow one to estimate the scattering phase function for the angles outside the small-angle range. The calculations were carried out for three distributions, each of which was a superposition of three lognormal modes with the parameters presented in Table 1.

Table 1. Parameters of the lognormal fractions

Parameter	Distribution		
	1st	2nd	3rd
N_1	$1.5\cdot10^9$	$1.5\cdot10^9$	$5.5\cdot10^9$
N_2	$6.8\cdot10^5$	$9.6\cdot10^5$	$2.4\cdot10^5$
N_3	$6.8\cdot10^4$	$4.8\cdot10^3$	$2.4\cdot10^4$
r_1	0.042	0.042	0.040
r_2	0.42	0.48	0.40
r_3	1.5	1.8	1.7
ν_1	0.55	0.55	0.53
ν_2	0.50	0.45	0.50
ν_3	0.78	0.68	0.70

N, r, and ν in Table 1 are the number density, median radius, and the standard deviation of the logarithms of the radius, respectively. The first distribution is the analytical approximation of the results of solving the inverse problem using data obtained in Oklahoma, USA in October 1995, the second is based on measurement data obtained on Spitsbergen Island in March 1997, and the third uses measurements at Zvenigorod Station of IAP RAS in July 1997.[4] These distributions, different in the ratio of the submicron and coarse aerosol fractions, were selected as typical for each region during the corresponding period of measurements. Particles with the radius less than 1 μm cause more than 75% of the aerosol optical thickness in the visible wavelength range in the first case, and more than 90% in the second and third cases.

Comparison of the angular dependences of light scattering coefficients at the wavelength of 0.53 μm corresponding to the distributions 1–3 with the calculated data on the optical thickness is presented in Figs. 1 and 2. The inverse problem was solved using the modified Twitty algorithm.[4]

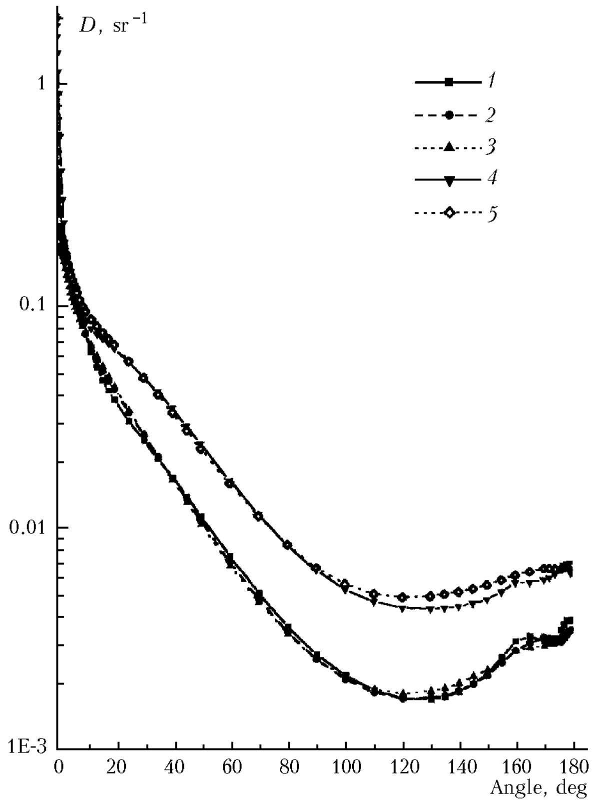

Fig. 2. Scattering phase function for the distributions 2 (curves *1–3*) and 3 (curves *4–5*): calculation for the distributions (*1*, *4*); solution of the inverse problem for AOT (*5*); calculation for inverse power distribution (*3*).

It follows from Figs. 1 and 2 that the differences in the range of the scattering angles 20 to 150° do not exceed 15%. The data on spectral AOT do not allow us to determine the aerosol refractive index n. The coefficients of directed light scattering were calculated for the initial distributions assuming $n = 1.48$. As is shown in Fig. 2, the improper choice of n in the range from 1.48 to 1.55 does not significantly affect the accuracy of microphysical extrapolation. Finally, one can estimate the scattering phase function without solving the inverse problem if calculating the Angström index and the scattering phase function for the inverse power distribution corresponding to this index. Thus calculated result is shown in Fig. 1. One should note that in calculating the sky brightness, the errors in setting the scattering phase function are partially smoothed due to the noticeable contribution of the molecular scattering at great scattering angles.

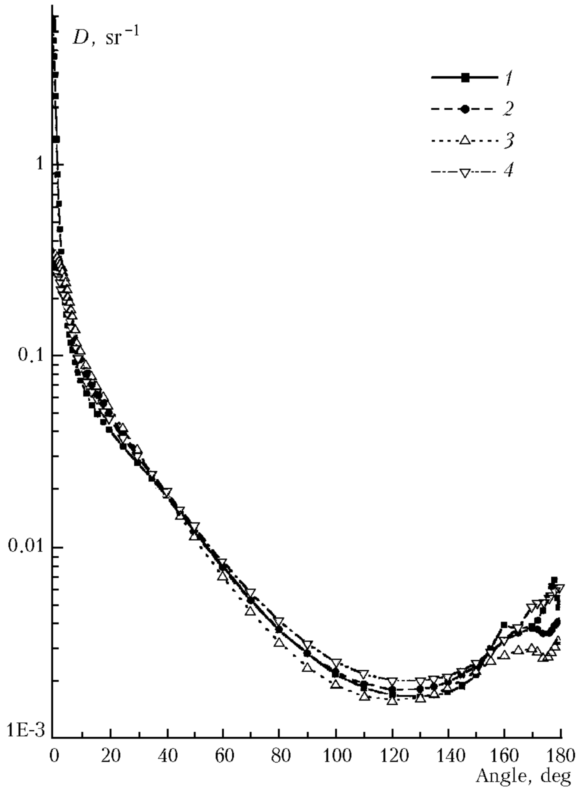

Fig. 2. Scattering phase functions for the distribution 1: calculation for the distribution (*1*) and solution of the inverse problem for AOT (*2–4*; *2* is for $n = 1.48$, *3* is for $n = 1.4$, and *4* is for $n = 1.55$).

A simple iteration algorithm can be suggested for determination of the single scattering phase function in the aureole range.

1. The inverse problem is solved (or the Angström index is determined) from the data on spectral AOT, and the angular dependence of the directed light scattering coefficients is calculated.
2. The sky brightness in the aureole range and the ratio of single scattering to the total one at the angles, at which measurements were carried out, are calculated by the Monte Carlo method.
3. The measured sky brightness is multiplied by this ratio and is accepted as an approximation of the single scattering brightness.
4. The single scattering phase function is transformed according to item 3.
5. If necessary, items 2 to 4 are repeated.

The analysis shows that no more than two iterations are enough at $\tau m < 1$ (τ is the optical thickness of the atmosphere, and m is the air mass in the direction toward the Sun). The method remains acceptable at high turbidity of the atmosphere. Let us present, as an example, the results on directed light scattering coefficients D determined for the distribution 3 at the wavelength of 0.46 μm. In modeling, m was taken equal to 5.8, and τ was 1. Table 2 shows the calculated results on the coefficients of directed light scattering from AOT (first column), the changes in D during the iteration process (columns 2 to 5), and their exact value (column 6) for three scattering angles.

As it follows from Table 2, the necessary number of iterations increases as the scattering angle decreases. Let us note that the portion of single scattering for the considered model situation is 45% for the angle of 1.9°, and 20% for 10.3°.

Table 2. Iteration reconstruction of the scattering phase function

Angle, deg.	Coefficient of directed light scattering					
	1	2	3	4	5	6
1.9	0.76	1.02	1.21	1.31	1.34	1.39
2.6	0.73	0.82	0.88	0.90	0.91	0.91
10.3	0.42	0.41	0.41	0.40	0.39	0.38

2. On the possibility of inverting the aureole measurements without taking into account multiple scattering

The sky brightness component caused by multiple scattering and reflection from the earth's surface has significantly lower asymmetry than that of the single scattering, and is characterized by a well-pronounced spectral selectivity (decreases as the wavelength increases). Therefore, ignoring the contribution from multiple scattering in inverting aureole measurements at not very high turbidity of the atmosphere leads to distortion of the obtained particle size distribution only in the size range less or comparable with the wavelength, where otherwise the aureole measurements have small information content. Thus, the size spectrum can be obtained by sewing together the results of inverting the spectral transparency of the atmosphere (submicron fraction) and the sky brightness field in the aureole range overburdened with multiple scattering (coarse fraction).

Our calculations have shown that such an approach is acceptable, at least, up to $\tau m = 2$. Distribution 1 is compared with the results of inversion of the aureole brightness and AOT in Fig. 3. Calculations were performed for $m = 5.8$. The straight line (on the logarithmic scale) corresponding to the inverse power distribution with the exponent determined from the Angström index is also shown in Fig. 3. The distributions are presented in the form $S(r) = \text{p}r^2\text{d}N/\text{d}r$, where $\text{d}N/\text{d}r$ is the number density distribution.

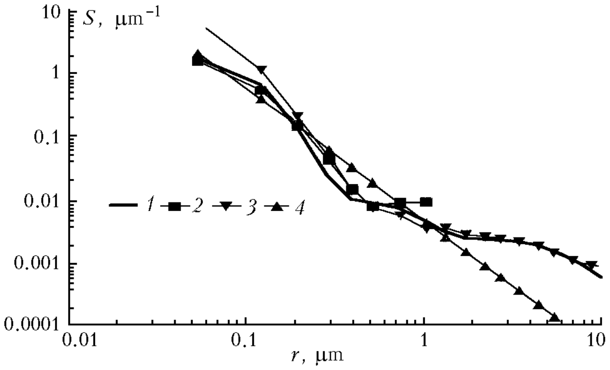

Fig. 3. Solution of the inverse problem without subtracting the background due to multiple scattering: the initial distribution (*1*), solution of the inverse problem for AOT (*2*), and inversion of the aureole brightness phase functions (*3*).

As was noted above, spectral measurements of the atmospheric transparency do not allow the estimate of the refractive index of aerosol substance to be obtained. One can estimate possible errors due to incorrect setting of the refractive index from the data shown in Fig. 4, where the results are shown of solving the inverse problem from AOT for the distribution 2 with the refractive indices $n = 1.4$ (curve *1*), 1.48 (*2*), and 1.55 (*3*). The change in the refractive index set *a priori* leads to a regular displacement of the distribution while keeping its shape. The differential number densities corresponding to $n = 1.4$ and $n = 1.55$ are different by no more than two times.

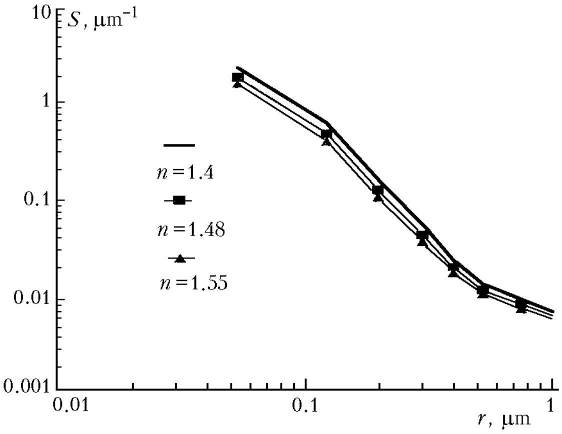

Fig. 4. The effect of selection of the refractive index on the retrieved aerosol size spectrum.

3. Interpretation of the results of observations

The approaches described above were used for processing the results of observations carried out in March 2001 at Zvenigorod Scientific station of IAP RAS. Aureole measurements were performed with the aureole sun photometer constructed on the basis of the Kvarts-4 opto-acoustic spectrometer.[4] The range of scattering angles was 2 to 10°, the range of wavelengths was 0.46 to 0.75 μm. Measurements of the optical thickness were performed simultaneously by means of the MFRSR device at five wavelengths in the range from 0.415 to 0.869 μm.

The brightness phase functions were extrapolated to the range of angles less than 2° by means of microphysical extrapolation, i.e., the inverse problem was solved for the measured brightness phase functions, and the "nose" of the scattering phase function was calculated for the distribution obtained. The model estimates have shown that such a way leads to a noticeable distortion of the final results. The results obtained by processing one of the measurements on March 27, 2001, are shown in Fig. 5, as an example. The air mass changed during the measurement cycle in the range $m = 3.5–3.4$. The aerosol optical thickness τ_{aer} was 0.23 at the wavelength of 0.415 μm and 0.07 at 0.869 μm. The single scattering albedo was taken to be equal to 0.3.

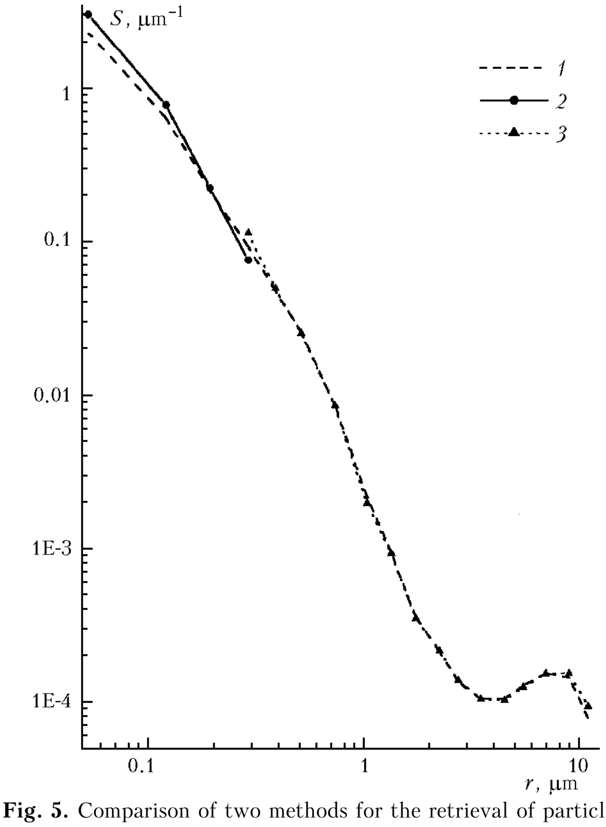

Fig. 5. Comparison of two methods for the retrieval of particle size distribution. Zvenigorod, March 27, 2001.

Figure 5 shows the size spectrum obtained at joint inverting the spectral transparency and the scattering phase functions retrieved by the method described in section 2 (curve *1*) and the synthetic spectrum resulting from "sewing" the distributions corresponding to the spectral dependence of AOT and the aureole spectral brightness (curve *3*) at the point $r = 0.3$ μm.

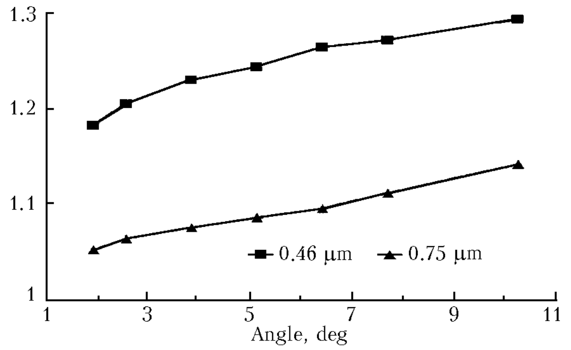

Fig. 6. Angular dependences of the ratio of the aureole brightness to the brightness caused by single scattering.

The angular behavior of the ratio of the brightness phase function to the single scattering phase function is shown in Fig. 6 for two wavelengths (0.46 and 0.75 μm).

Conclusion

The approaches described in this paper can be useful, in our opinion, for interpretation of aureole measurements under conditions of a turbid atmosphere. They certainly are not acceptable in situations with the prevalent scattering on coarse aerosol. The AOT behavior close to neutral in these conditions is not informative relative to the parameters of the aerosol microstructure. The second restriction is related to the aerosol absorption properties. We made our calculations assuming that the aerosol absorption is absent. If the single scattering albedo has been significantly less than unity, it is necessary to attract the additional data on real and imaginary parts of the refractive index of the aerosol substance.

Acknowledgments

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