Methods for correcting the atmospheric aerosol optical depth along horizontal and slant paths

N.N. Shchelkanov

Institute of Atmospheric Optics, Siberian Branch of the Russian Academy of Sciences, Tomsk

Received September 1, 2005

Three improved methods of correction of atmospheric aerosol optical depth (AOD) are presented. The first method implies determination of absolute AOD values or their relative spectral behavior in several spectral regions. The method allows one to reveal and remove systematic errors from AOD values. The second method implies availability of absolute AOD values in just one spectral region; in other spectral regions the AOD values are corrected. The third method is used in the case when no absolute AOD values or their relative spectral behavior are available. It is called "zero-point" method and assumes zeroing of minimum AOD value in one spectral region. To relate different AOD values in different spectral regions, these new methods use a generalized linear regression formula derived taking into account random errors in the data used.

Introduction

The experimental studies of aerosol extinction in ultraviolet, visible, and infrared spectral regions have as their primary objective to separate correctly this component from the total extinction. Usually, for determination of atmospheric aerosol optical depth (AOD) $\tau(\lambda)$ most researchers use the "residual principle," that is when $\tau(\lambda)$ is determined as the difference between the total atmospheric optical depth $\varepsilon(\lambda)$ and the molecular extinction components. Because of the use of different methods to allow for the molecular extinction components, different aerosol extinction values are obtained. For instance, different versions of HITRAN program[1,2] give diverging extinction values. In addition, the use of "residual principle" leads to introducing the systematic error of $\varepsilon(\lambda)$ to $\tau(\lambda)$. All these factors may substantially distort both $\tau(\lambda)$ values and their spectral behavior. This motivates the development of the methods capable of removing the disadvantages of "residual principle" of separation of the aerosol extinction component both for the cases of horizontal and slant paths.

In Ref. 3 we have suggested the methods of correction of spectral behavior of atmospheric aerosol optical depth. To determine the relation between atmospheric aerosol optical depths at neighboring wavelengths, these methods use the coefficients of orthogonal least squares linear regression equation.[4] In Ref. 5 it is shown that these coefficients are obtained from the generalized formula of linear regression provided that (1) the scatter of points in the correlation of these quantities at two neighboring wavelengths is caused only by random measurement errors, and (2) that these errors are identical in the spectral region studied. Note that the first condition is satisfied only approximately, while the second one is not always satisfied in the entire spectral region under study. For instance, as was argued in Ref. 6, the random rms error of measurements of the aerosol extinction coefficient along a 4.63-km long path in the wavelength region from 0.44 to 1.06 μm is ~0.007 km^{-1}, while in the wavelength region from 1.6 to 12 μm it exceeds 0.011 km^{-1}. Therefore, in the wavelength region from 1.6 to 12 μm the use of the methods suggested in Ref. 3 will lead to overestimation of aerosol extinction coefficients. Therefore, in the following sections we present improved methods for correcting the AOD.

1. Physical grounds of the methods

Suppose that we have an array of atmospheric aerosol optical depth values obtained by subtracting the molecular components from the total extinction. To perform the correction, the total $\tau(\lambda)$ array is used to form the correction array; it includes either all experimental data or their part and satisfies the following conditions:

1. The presence of linear relation and significant correlation between atmospheric aerosol optical depths in the entire spectral region studied. Check on the linearity of the relation is made by the least squares method.[4] If nonlinearity will be found for large $\tau(\lambda)$ values, these points must be excluded from the considered array. As a rule, the correction array includes the spectra with values $\tau(\lambda) < 0.2$.

2. Availability in the correction array, in addition to other $\tau(\lambda)$ values, of the $\tau(\lambda)$ values, which are equal or close to zero within the error of a single measurement in the entire spectral region studied. It should be noted that this requirement is to be checked after $\tau(\lambda)$ correction. This requirement is necessary as a linearity check of relation between atmospheric aerosol optical depths in the case of their closeness to zero.

To determine the relation between the atmospheric AODs at different wavelengths, we use the least squares linear regression equation

$$\tau_j = K_{0ij} + K_{ij}\tau_i, \quad (1)$$

where i, $j = 1, 2, \ldots, n$; n is the number of studied spectral intervals; and τ_i and τ_j are the atmospheric aerosol optical depths at the wavelengths λ_i and λ_j. In their turn, the regression coefficients K_{ij} are determined from the generalized formula[5]:

$$K_{ij} = \frac{\sigma_j}{\sigma_i}\frac{B}{A}\frac{1}{2\rho_{ij}}\left\{\left(\frac{A}{B}-\frac{B}{A}\right)+\sqrt{\left(\frac{A}{B}-\frac{B}{A}\right)^2+4\rho_{ij}^2}\right\}, \quad (2)$$

where

$$A = \sqrt{1-|\rho_{ij}|\sqrt{\frac{1-\delta_{ij}^2/\sigma_i^2}{1-\delta_{ji}^2/\sigma_j^2}}}; \qquad B = \sqrt{1-|\rho_{ij}|\sqrt{\frac{1-\delta_{ji}^2/\sigma_j^2}{1-\delta_{ij}^2/\sigma_i^2}}}; \quad (3)$$

ρ_{ij} are the normalized coefficients of correlation between τ_i and τ_j; σ_i and σ_j are their standard deviations; δ_{ij} and δ_{ji} are the random rms measurement errors in τ_i and τ_j for the considered data array relative to τ_j and τ_i.

Physically, the fact that the K_{0ij} coefficients equal zero means that if concentrations of optically active submicron and coarse aerosol are zero, the atmospheric aerosol optical depths must be zero too in the entire spectral region studied. Thus, if the regression coefficients K_{0ij} in formula (1) for correction array are nonzero, then correction of AOD and its spectral behavior is needed.

Obviously, the mean corrected values of atmospheric aerosol optical depth $\bar{\tau}'$ for calibration array will be related by the formula

$$\bar{\tau}_1' = K_{12}\bar{\tau}_2' = K_{12}K_{23}\bar{\tau}_3' = \ldots = K_{12}K_{23}\ldots K_{n-1,n}\bar{\tau}_n', \quad (4)$$

while the corrected and non-corrected τ values by the formula

$$\bar{\tau}_i' = \bar{\tau}_i - \Delta_{0i}, \quad (5)$$

where Δ_{0i} is the systematic error at the ith wavelength ($i = 1, \ldots, n$). The systematic error Δ_{0i} can be conventionally divided into two parts:

$$\Delta_{0i} = \Delta_0 + \Delta_i. \quad (6)$$

The first part, Δ_0, is constant for all spectral regions being caused by a common factor. One such factor in measurements of the aerosol extinction along horizontal paths can be imprecise determination of lengths of measurement (long) and calibration (short) atmospheric paths. The second part, Δ_i, has different absolute values, may be sign-alternating, and is caused by the presence of random errors in measurements of signals along the calibration path.

In context of the correction of AOD value, three methods can be formulated.

2. Method of determination of systematic errors in AOD

The first method implies determination of absolute values of "zero signals" or their relative spectral behavior in several spectral regions. Here, by "zero signal" is meant the intensity I_0 of radiation in the beginning of the measurement path; this quantity is defined by Bouguer law as $I = I_0\exp(-\tau)$. For τ correction, it is necessary to choose the spectral intervals where the extinction is determined only by aerosol (excluding Rayleigh scattering), or where the molecular extinction component can be taken into account with an acceptable accuracy. In other parts of the spectrum, the "zero signals" at the first stage can be taken arbitrary, while the method of determination of corrections at these wavelengths will be outlined in section 3.

The systematic errors Δ_0 and Δ_i are determined from conditions of minimum of the sum

$$\psi = \sum_{i=1}^{n}\left(K_i - \frac{\bar{\tau}_i - \Delta_0}{\bar{\tau}_1 - \Delta_0 - \Delta_1}\right)^2 \quad (7)$$

and the zero-valued sum

$$\sum_{i=1}^{n}\left(K_i - \frac{\bar{\tau}_i - \Delta_0}{\bar{\tau}_1 - \Delta_0 - \Delta_1}\right) = 0, \quad (8)$$

where the coefficients

$$K_i = \bar{\tau}_i'/\bar{\tau}_1' = 1/\prod_{j=1}^{i-1}K_{j,j+1} \quad (9)$$

represent the relative spectral behavior of the mean corrected values of coefficients of atmospheric AOD for the correction array. From formula (8) we obtain

$$\Delta_1 = \bar{\tau}_1 - \Delta_0 - \left[\left(\sum_{i=1}^{n}\bar{\tau}_i - n\Delta_0\right)/\sum_{i=1}^{n}K_i\right]. \quad (10)$$

Substituting expression (10) in Eq. (7) and equating the first derivative of the sum ψ with respect to Δ_0 to zero, we obtain the formula for Δ_0 determination:

$$\Delta_0 = \frac{\sum_{i=1}^{n}\bar{\tau}_i\sum_{i=1}^{n}K_i\bar{\tau}_i - \sum_{i=1}^{n}K_i\sum_{i=1}^{n}\bar{\tau}_i^2}{n\sum_{i=1}^{n}K_i\bar{\tau}_i - \sum_{i=1}^{n}K_i\sum_{i=1}^{n}\bar{\tau}_i}. \quad (11)$$

The other errors Δ_i ($i = 2, \ldots, n$) are determined from the formula

$$\Delta_i = \bar{\tau}_i - \Delta_0 - K_i(\bar{\tau}_1 - \Delta_0 - \Delta_1). \quad (12)$$

3. Correction method of spectral AOD variations

The second method is based on the use of τ at a single (jth) wavelength as the initial value; it allows one to determine the "zero signal" only in this spectral interval. In other parts of the spectrum, the "zero signals" are chosen arbitrary, while the obtained τ values are corrected.

Corrections to the atmospheric aerosol optical depths at a current wavelength are determined from the formula

$$\Delta\tau_i = \bar{\tau}_i - \frac{K_i}{K_j}\bar{\tau}_j. \quad (13)$$

The absolute values of systematic errors introduced by such an approach to the atmospheric aerosol optical depths at the ith wavelength are

$$\Delta_{0i} = \frac{K_i}{K_j}(\Delta_0 + \Delta_j), \quad (14)$$

and the relative values

$$\frac{\Delta_{0i}}{\bar{\tau}_i'} = \frac{\Delta_0 + \Delta_j}{\bar{\tau}_1' K_j}, \quad (15)$$

where $\Delta_0 + \Delta_j$ is the systematic error at the initial wavelength. Obviously, it is necessary to choose as the initial spectral interval the one in which the relative error is minimum. If the systematic errors $\Delta_0 + \Delta_j$ ($j = 1, ..., n$) are close in different spectral intervals, as is typical under real atmospheric conditions, then formula (15) reaches minimum for maximum coefficient K_j or maximum aerosol optical depth τ_i'. Then, in τ measurements in a wide spectral region it is necessary to choose as the initial region the shortwave part of the spectrum.

4. AOD determination by the method of "zero point"

The third method of "zero point" implies zeroing of minimum AOD value in a single interval of the spectral region studied. This method can be used in the absence of "zero signals" in the entire spectral region studied or when the arrays of experimental data have negative AOD values coming out beyond the limits of random AOD calculation error.

The procedure of determination of absolute τ values is as follows. We specify arbitrary "zero signals" for all spectral intervals, take τ at any wavelength as the initial value, and use the method outlined in section 3 to determine the corrected values of atmospheric AOD. Thus obtained array contains a spectral interval in which the smallest τ values are obtained; they are checked on confidence and inspected to select minimum value to be set to zero. Suppose that the minimum τ value is found to be τ_{0j}. Then the corrected mean τ value at the jth wavelength is

$$\bar{\tau}_j' = \bar{\tau}_j - \tau_{0j}. \quad (16)$$

The τ corrections at other wavelengths are determined from the formula

$$\Delta\tau_i = \bar{\tau}_i - \frac{K_i}{K_j}(\bar{\tau}_j - \tau_{0j}), \quad (17)$$

while the current corrected atmospheric AOD values are evaluated by the following formula

$$\tau_i' = \tau_i - \bar{\tau}_i + \frac{K_i}{K_j}(\bar{\tau}_j - \tau_{0j}). \quad (18)$$

Thus obtained values represent the upper estimate of τ.

It should be noted that this approach can only be used if quite long-time observation series of τ are available, because the longer the time series, the higher the probability of near-zero τ values to occur in the spectral region studied. Argument in favor of the usability of this approach may be the presence in experimental arrays of τ values which are equal or close to zero within the random error of single ε measurement.

Conclusion

Thus, the proposed correction methods allow one to determine the absolute values of atmospheric aerosol optical depths without calibration of a measurement device in the entire spectral region studied, as well as to reveal possible systematic errors in separation of aerosol extinction by classical methods.

Acknowledgments

This work has been done in the framework of the program of scientific school of M.V. Kabanov, Corresponding Member of RAS (NSh-1008.2003.5).

References

1. L.H. Giver, C.Jr. Chackerian, and P. Varanasi, J. Quant. Spectrosc. Radiat. Transfer **66**, 101–105 (2000).
2. L.S. Rothman, A. Barbe, D. Chris Benner, L.R. Brown, C. Camy-Peyret, M.R. Carleer, K. Chance, C. Clerbaux, V. Dana, V.M. Devi, A. Fayt, J.-M. Flaud, R.R. Gamache, A. Goldman, D. Jacquemart, K.W. Jucks, W.J. Lafferty, J.-Y. Mandin, S.T. Massie, V. Nemtchinov, D.A. Newnham, A. Perrin, C.P. Rinsland, J. Schroeder, K.M. Smith, M.A.H. Smith, K. Tang, R.A. Toth, J. Vander Auwera, P. Varanasi, and K. Yoshino, J. Quant. Spectrosc. Radiat. Transfer **82**, 5–44 (2003).
3. N.N. Shchelkanov, Atmos. Oceanic Opt. **7**, No. 7, 468–470 (1994).
4. A.N. Zaidel, *Measurement Errors of Physical Quantities* (Nauka, Moscow, 1985), 112 pp.
5. N.N. Shchelkanov, Atmos. Oceanic Opt. **18**, Nos. 1–2, 77–81 (2005).
6. N.N. Shchelkanov, "*Study of extinction of optical radiation by aerosol and water vapor in the atmosphere of arid zone*," Author's Abstract of Cand. Phys.-Math. Sci. Dissert., IAO SB RAS, Tomsk (1977), 22 pp.