NOTES and CORRESPONDENCE
Forward Scattering Effect on the Estimation of the Aerosol Optical Thickness for Sun Photometry

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Abstract

Accurate aerosol optical thickness is indispensable for estimating the radiative forcing of aerosols in the atmosphere. Sun photometry is one of the most popular methods, which is simple and easy to use, but it should be noted that some errors due to forward scattering effect can be introduced in the observation of direct normal irradiance. Consequently, the estimated optical thickness of aerosols can be underestimated even if the calibration constant is correct. This possibility depends on an optical geometry of the measuring instrument as well as aerosol characteristics. This report assesses these effects by assuming several aerosol types and instrumental parameters quantitatively.

Forward scattering ratio \( \gamma_{\lambda,\text{fwd}} \), which is defined as a ratio of the forward scattering part to the true direct normal irradiance \( I_\lambda \), by \( I_{\lambda,\text{obs}} = I_\lambda (1 + \gamma_{\lambda,\text{fwd}}) \), is approximately proportional to the product of the optical thickness \( \tau_{\lambda,\text{aer}} \) and the single scattering albedo \( \omega_\lambda \) of aerosols and the relative air mass \( m \), \( \gamma_{\lambda,\text{fwd}} \approx \varepsilon_\lambda \omega_\lambda \tau_{\lambda,\text{aer}} m \). The coefficient \( \varepsilon_\lambda \) is a proportional constant which is dependent on the opening angle of the instrument as well as the optical characteristics of aerosols. The variation of \( \varepsilon_\lambda \) is tabulated for several aerosol types and opening angles. Then, the error of the estimate of \( \tau_{\lambda,\text{aer}} \) can be approximately expressed by \( \Delta \tau_\lambda \approx -\varepsilon_\lambda \omega_\lambda \tau_{\lambda,\text{aer}} m \).

Keywords aerosol; forward scattering; sun photometry; opening angle

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1. Introduction

Climate effects of particles suspended in the atmosphere have been studied by many researchers for a long time because of their importance (e.g., Charlson and Heintzenberg 1995; Hobbs 1993; IPCC 2014). These effects consist of two major aspects as well known: one is a direct effect, and the other is an indirect effect. The recent focus of aerosol studies on climate change has been mainly on the latter effects as these show a variety of mechanism in the atmosphere and are still not clear. On the other hand, the direct effect is easily understandable through the assessment of radiative effects, among which are the following parameters: the optical characteristics, i.e., the optical thickness (AOT), the single scattering albedo (SSA), and so on are estimated by using a combination of the size distribution and the complex refractive index of the particles. Ground-observation networks for aerosol and cloud, such as AERONET (https://aeronet.gsfc.nasa.gov) and SKYNET (http://atmos3.cr.chiba-u.jp/skynet/), have been introduced in parallel with satellite monitoring. These network observations can give detailed and useful information on aerosols world-
wide. This information is based on the sky brightness measurements, including the direct solar irradiance (e.g., Giles et al. 2019; Kitakoga et al. 2014).

The AOT has been estimated experimentally by sun photometry. This method is reliable and has a long history because of its ease of use (e.g., Voltz 1974; Shaw 1983). A sun photometer has been designed and used in order to estimate it, as well as the water vapor and ozone amounts. The field of view (FOV) of the instrument is limited to an angle wide enough to measure the attenuated irradiance from the solar disk. Grassl (1971) pointed out that the effect of circum-solar irradiance should be corrected when a photometer has a wider FOV. In another aspect, the instrument needs to follow the motion of the solar disk correctly. Regarding the accuracy of the AOT estimate, the smaller FOV is better, but a wider FOV is required for tracking the sun steadily. This is a trade-off. For example, the WMO document (World Meteorological Organization 2012) provides the FOV angle for an observation instrument such as a pyrheliometer in order to minimize the effect of forward scattering. In addition, the improved solar tracking technique can possibly make less forward scattering measurements for direct solar observations.

In this report, the effects of forward scattering on the AOT estimate using the sun photometry technique are discussed quantitatively and qualitatively.

2. Error by forward scattering

The basic concept in estimating the AOT is simply to use the incoming direct solar irradiance (DNI) attenuated by aerosols at wavelengths without any gaseous absorption. When such wavelengths are selected, the observed irradiance \( I_{\text{obs}} \), including forward scattering in the clear atmosphere, can be converted to an apparent atmospheric optical thickness \( \tau_{\text{app}} \) of aerosol and molecular scattering. These parameters are a function of wavelength, but it is omitted to avoid complexity hereafter. If the calibration constant of the used instrument is assumed to be \( F_0^* \), including the calibration error, the observed DNI, \( I_{\text{obs}} \), can be expressed by using the apparent optical thickness \( \tau_{\text{app}} \):

\[
I_{\text{obs}} = F_0^* e^{-\tau_{\text{app}} m},
\]

then,

\[
\tau_{\text{app}} = \tau + 1/m \cdot \ln(\gamma_{\text{cal}}/(1 + \gamma_{\text{fwd}})).
\]

The parameter of the distance between the Earth and the sun is also omitted in the equation. The variable \( m \) is the relative air mass corresponding to the solar position. The true values of the calibration constant and the atmospheric optical thickness are \( F_0 \) and \( \tau \), respectively. \( \gamma_{\text{fwd}} \) in Eq. (2) is the ratio of the forward scattering part \( \Delta I_{\text{fwd}} \) in the \( I_{\text{obs}} \) to the true DNI, and \( \gamma_{\text{cal}} \) is the ratio of the actual calibration constant to the true one:

\[
I_{\text{obs}} = I + \Delta I_{\text{fwd}} = I(1 + \gamma_{\text{fwd}}),
\]

and

\[
F_0^* = \gamma_{\text{cal}} F_0.
\]

Then, the difference \( (\Delta \tau) \) between the atmospheric optical thickness and the true value is expressed by the second term on the right-hand side of Eq. (2).

Figure 1 shows the value of \( \ln(\gamma_{\text{cal}}/(1 + \gamma_{\text{fwd}})) \) in Eq. (2), which is equal to the difference \( (m\Delta \tau) \). Even if the calibration constant is correct \( (\gamma_{\text{cal}} = 1) \), forward scattering leads to an under-estimation of the optical thickness as expected. In general, the erroneous calibration can produce both negative (under-estimation) and positive (over-estimation) effects. Therefore, the line without error is apparently due to the cancellation of these effects. Note that the vertical axis of Fig. 1 is a logarithmically arbitrary unit (not correct logarithmic scale).

The amount of actual forward scattering must be proportional to the scattering part of the optical thickness under a single scattering assumption, i.e., \( \omega \tau \), when the scattering pattern is the same at varying AOTs. However, since the pattern will change depend-
ing on the weighted ratio of each part of the Rayleigh and aerosol scattering, the forward scattering ratio can be approximately expressed as $\gamma_{fwd} \approx \varepsilon_\omega \tau_{aer} m$ for $\gamma_{fwd} \ll 1$. Therefore, the logarithmic equation of the true DNI is approximately expressed as follows:

$$\ln I \approx \ln F_0^* - (\tau_{app} + \varepsilon_\omega \tau_{aer}) m,$$  \hspace{0.5cm} (4)

and if the calibration constant is correct, $F_0^* = F_0$,

$$\tau_{app} = \tau - \varepsilon_\omega \tau_{aer} \approx \tau (1 - \varepsilon_\omega).$$  \hspace{0.5cm} (5)

The variable $\varepsilon$ in Eqs. (4) and (5) is a proportional coefficient, which will be dependent on the aerosol type and the instrumental geometry. Forward scattering can reduce the optical thickness by roughly $(1 - \varepsilon_\omega)$ when the Rayleigh scattering by atmospheric molecules is negligible. Therefore, the underestimate of $\tau_{app}$ is dependent on the atmospheric turbidity and the quality of aerosols of the observation day.

2.1 Effect to instrument calibration

When an instrument is calibrated using the Langley method, the forward scattering effects also appear in the DNI observation. A calibration constant estimated by the Langley method, however, should not be affected under stable atmospheric conditions. Even if the optical thickness has an error due to forward scattering, the Langley plot can produce the correct calibration constant $F_0$ because $\gamma_{fwd} = 0$ at $m = 0$, as shown in Fig. 2. The broken lines in the figure depict the slopes of the Langley plot used to estimate the calibration constant, of which slopes are the optical thicknesses, $\tau_{app}$ and $\tau$, respectively. The difference between $\ln I_{\lambda, app}$ and $\ln I$ at a relative air mass $m$ is equal to $\ln (1 + \gamma_{fwd})$.

However, when the calibration is performed by comparing a sample instrument with a reference one at any optical thickness of the atmosphere, the scattering effect appears clearly as follows:

$$F_0 = F_0^{ref} (1 + \gamma_{obs})/(1 + \gamma_{ref}).$$ \hspace{0.5cm} (6)

In Eq. (6), $F_0^{ref}$ and $\gamma_{ref}$ are the calibration constant and the forward scattering ratio of the reference instrument, respectively.

2.2 Simulation by radiative transfer calculation

To assess the quantitative effect of forward scattering in the DNI observation, radiative transfer calculation is performed by using the SMARTS code developed by Gueymard (1995). The forward scattering effect of suspended particles is caused by two major sources, as described in the previous section. In the simulation, several typical cases for these parameters are assumed.

The input geometry of an instrument can primarily affect $\Delta I_{fwd}$ in Eq. (3). The FOV is defined by two parameters, namely, the opening half angle ($\theta$) and the slant angle (Vignola et al. 2012). The simulation is performed by assuming three typical cases, as shown in Table 1. The biggest case is introduced for an operational pyrheliometer ($2\theta = 5.0$), which is required by the WMO document (World Meteorological Organization 2012), and the smaller case of $2\theta = 1.0$ is used for sun/sky radiometers of the SKYNET observation (http://atmos3.cr.chiba-u.jp/skynet/). An opening angle of $2\theta = 2.0$ is assumed for collimating direct solar radiation when calibrating a spectral radiometer (pyranometer).

Different types of aerosols can contribute differently to scattering, as it is well known (van de Hulst 1981). In the assessment of quantitative and qualitative effects, three aerosol models are taken into consideration for the simulation by selecting the “S&F Urban” and the “S&F Maritime” models by Shettle and Fenn (1979) and the “Desert-Max” model seen in strong dust storms (Gueymard, Manual for SMARTS2.9.5: https://www.nrel.gov/grid/solar-resource/smarts.html). The “S&F Urban” model is typical for a polluted atmosphere, which has secondary particles rich in size distribution and a smaller single scattering albedo (SSA). On the other hand, there are lots of coarse/
natural particles in the “Maritime” model which are composed of very light absorptive particles (SSA is close to 1). The “Desert-Max” model might not be popular in a usual atmosphere, but it is one of the special cases with lots of coarse particles in the desert and its downwind regions. These three models have unique optical characteristics, as shown in Fig. 3.

Six steps of AOT for each model ($\tau_{aer}$: 0.01, 0.05, 0.1, 0.2, 0.5, and 1.0 at 500 nm) are used in the simulation. Figure 3 shows the wavelength dependence of AOT (Fig. 3a) for each model with values of 0.2 and 1.0 at 500 nm. The largest Angstrom Exponent (AE; $\alpha$) is from the “S&F Urban” model, and the mid value is that of the “S&F Maritime” model. The “Desert-Max” model has $\alpha = 0$, which means that the AOT shows no wavelength dependence. Therefore, the coarse particles are relatively more abundant than those in the other two models. The wavelength dependence of SSA is also shown in Fig. 3b. The “S&F Maritime” model has a very weak absorption along the whole wavelength range compared with the other two models. An artificial bump in SSA at 500 nm is found for the “Desert-Max” model. The “Mid-Latitude Summer” model (McClatchey et al. 1971) is used as an atmospheric model with a standard pressure of 1013.25 hPa at the surface. Other atmospheric parameters are shown in Table 2. The wavelengths for calculation range from 300 to 1100 nm for the effective region of scattering in the usual atmosphere. The solar position is also made to vary between three relative air masses: $m = 1.0$ (solar zenith angle: $\text{sza} = 0^\circ$), $m = 3.0$ (sza = 70.7°), and $m = 5.0$ (sza = 78.8°).

3. Results and discussion

The forward scattering ratios $I_{\text{fwd}}$ are calculated for 11 models built in the SMARTS code to compare the differences between the aerosol models, as shown in Fig. 4. That figure presents only cases for a relative air mass (AM) $m = 5$ and an opening angle (OA) $2\theta = 5.0^\circ$. Each model has the same AOT of 0.2 at 500 nm. In Fig. 4a, the “S&F Maritime” model shows the biggest contribution of $I_{\text{fwd}}$ among the 11 models. Regarding the difference in the AE, “Desert-Max” (Fig. 4c) is supposed to be the most effective, but “S&F Maritime” is the largest because of its high SSA. “Desert-Max” has also relatively larger values compared to those of the others, except for “SRA-Maritime”. “S&F Urban” (Fig. 4a) does not

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Table 1. Assumed parameters in FOV of an instrument. The definition of each angle is referred in Vignola et al. (2010).

| Opening angle ($2\theta$ (deg)) | Slope angle (deg) | Limiting angle (deg) | Instrument (Example) |
|--------------------------------|-------------------|----------------------|---------------------|
| 5.0                           | 1.0               | 4.0                  | Operational pyrheliometer |
|                                |                   |                      | e.g., CHP-1 (Kipp & Zonen), MS-54 (EKO) |
| 2.0                           | 0.4               | 1.6                  | Collimation tube for calibration of spectral radiometer/pyranometer |
| 1.0 ($^*$)                    | 0.2               | 0.8                  | Sun photometer/Sky radiometer |
|                                |                   |                      | e.g., POM-02(PREDE), ($^*$) 1.2 deg for CE318 (CiMEL) |

Fig. 3. Optical characteristics of three aerosol models used in the simulation. The left figure (a) shows the wavelength dependence of two AOTs of 0.2 and 1.0 at 500 nm. The right figure (b) is the same, except for SSA.
have the lowest value, but it is applied because it is the most popular type in urbanized areas. The three models, namely, “S&F Maritime”, “S&F Urban”, and “Desert-Max”, are selected in the analysis. The characteristics of eight models not selected in the simulation are also shown in the manual of the SMARTS code (Gueymard, Manual for SMARTS2.9.5: https://www.nrel.gov/grid/solar-resource/smarts.html).

The dependency of $\gamma_{fwd}$ on the actual optical thickness for the line of sight at 500 nm for the “Desert-Max” aerosol model. The optical geometry is for an opening angle of 5.0°. The red squares show a variation of $\gamma_{fwd}$ as a function of AOT $\times$ SSA $\times$ AM ($\tau_{aer, ocm}$), and the black dots are the same, except for a function of AOT $\times$ AM ($\tau_{aer, m}$) as a reference.

Table 2. Atmospheric model and parameters in the simulation.

| Atmospheric Model         | Surface reflectance | Water vapor | Carbon dioxide | Ozone | Other minors |
|---------------------------|---------------------|-------------|----------------|-------|--------------|
| Mid Latitude Summer       | 0.1                 | 29.8 mm     | 400 ppm        | 300 DU| SMARTS2.9.5  |
| Default values            |                     |             |                |       |              |

Fig. 4. Wavelength dependence of forward scattering ratio $\gamma_{fwd} = \Delta I_{fwd}/I_{DNI}$ as a function of wavelength in nm for 11 aerosol models (4a to 4c) built in the SMARTS2.9.5 code. The characteristics of each aerosol model are described in the manual (https://www.nrel.gov/grid/solar-resource/smarts.html). All graphs are only for air mass (AM) $m = 5$ and opening angle (OA) $2\theta = 5^\circ$. Each model has the same aerosol optical thickness of 0.2 at 500 nm.

Fig. 5. An example of the relationship between the scattering ratio $\gamma_{fwd} (= \Delta I_{fwd}/I_{DNI})$ and the aerosol (scattering) optical thickness in the line of sight at 500 nm for the “Desert-Max” aerosol model. The optical geometry is for an opening angle of 5.0°. The red squares show a variation of $\gamma_{fwd}$ as a function of AOT $\times$ SSA $\times$ AM ($\tau_{aer, ocm}$), and the black dots are the same, except for a function of AOT $\times$ AM ($\tau_{aer, m}$) as a reference.
red squares. In the figure, the variation of AOT × AM $(\tau_{aer} m)$ is shown in black dots as a reference. When the single scattering is dominant, these ratios should be basically proportional to the actual scattering optical thickness, and when the optical thickness is thinner, the linearity gets a little worse because of the relative increase of the Rayleigh scattering. However, the figure shows good proportionality. The equation of $\gamma_{fwd} \approx \varepsilon \omega \tau_{aer} m$ is reasonable, and the coefficient $\varepsilon$ is summarized in Table 3 for three models.

| Aerosol model Wavelength(nm) | Opening Angle: 5.0 deg., Slant Angle: 1.0 deg. | R2 | Desert-Max OA5.0:Coeff. R2 | S&F Maritime OA5.0:Coeff. R2 |
|-----------------------------|------------------------------------------------|----|-----------------------------|-----------------------------|
|                             | Urban OA5.0:Coeff.                              |    | Desert-Max OA5.0:Coeff.     | S&F Maritime OA5.0:Coeff.   |
| 315                         | 3.462E-02                                      | 0.9917 | 9.157E-02                  | 0.9957                      |
| 340                         | 3.307E-02                                      | 0.9965 | 8.787E-02                  | 0.9984                      |
| 400                         | 3.122E-02                                      | 0.9994 | 8.216E-02                  | 0.9998                      |
| 500                         | 3.005E-02                                      | 0.9999 | 7.590E-02                  | 1.0000                      |
| 675                         | 2.940E-02                                      | 1.0000 | 6.736E-02                  | 1.0000                      |
| 870                         | 3.119E-02                                      | 1.0000 | 5.886E-02                  | 1.0000                      |
| 940                         | 3.202E-02                                      | 1.0000 | 5.614E-02                  | 1.0000                      |
| 1020                        | 3.302E-02                                      | 1.0000 | 5.325E-02                  | 1.0000                      |

Table 3. The wavelength dependence of coefficient $\varepsilon$ for three kinds of opening angle ($2\theta$) and three aerosol models. The coefficient $\varepsilon$ is derived by $\varepsilon = \gamma_{fwd}/(\tau_{aer} o m)$. The term “R2” means the decision coefficient for each $\varepsilon$ estimation.

| Aerosol model Wavelength(nm) | Opening Angle: 2.0 deg., Slant Angle: 0.4 deg. | R2 | Desert-Max OA2.0:Coeff. R2 | S&F Maritime OA2.0:Coeff. R2 |
|-----------------------------|------------------------------------------------|----|-----------------------------|-----------------------------|
|                             | Urban OA2.0:Coeff.                              |    | Desert-Max OA2.0:Coeff.     | S&F Maritime OA2.0:Coeff.   |
| 315                         | 1.005E-02                                      | 0.9976 | 3.466E-02                  | 0.9993                      |
| 340                         | 9.793E-03                                      | 0.9990 | 3.287E-02                  | 0.9997                      |
| 400                         | 9.476E-03                                      | 0.9998 | 2.940E-02                  | 1.0000                      |
| 500                         | 9.276E-03                                      | 1.0000 | 2.506E-02                  | 1.0000                      |
| 675                         | 9.172E-03                                      | 1.0000 | 1.972E-02                  | 1.0000                      |
| 870                         | 9.144E-03                                      | 1.0000 | 1.553E-02                  | 1.0000                      |
| 940                         | 9.155E-03                                      | 1.0000 | 1.434E-02                  | 1.0000                      |
| 1020                        | 9.170E-03                                      | 1.0000 | 1.314E-02                  | 1.0000                      |

| Aerosol model Wavelength(nm) | Opening Angle: 1.0 deg., Slant Angle: 0.2 deg. | R2 | Desert-Max OA1.0:Coeff. R2 | S&F Maritime OA1.0:Coeff. R2 |
|-----------------------------|------------------------------------------------|----|-----------------------------|-----------------------------|
|                             | Urban OA1.0:Coeff.                              |    | Desert-Max OA1.0:Coeff.     | S&F Maritime OA1.0:Coeff.   |
| 315                         | 3.998E-03                                      | 0.9999 | 1.315E-02                  | 0.9997                      |
| 340                         | 3.885E-03                                      | 0.9996 | 1.223E-02                  | 0.9999                      |
| 400                         | 3.697E-03                                      | 0.9999 | 1.046E-02                  | 1.0000                      |
| 500                         | 3.481E-03                                      | 1.0000 | 8.423E-03                  | 1.0000                      |
| 675                         | 3.379E-03                                      | 1.0000 | 6.158E-03                  | 1.0000                      |
| 870                         | 3.169E-03                                      | 1.0000 | 4.590E-03                  | 1.0000                      |
| 940                         | 3.095E-03                                      | 1.0000 | 4.173E-03                  | 1.0000                      |
| 1020                        | 3.012E-03                                      | 1.0000 | 3.762E-03                  | 1.0000                      |
Figures 6a–c show the wavelength dependency of $\varepsilon$, and the OA dependency is shown in Figs. 6d–f for the three different OAs. Figures 6a and 6d are for “S&F Urban”, Figs. 6b and 6e are for “Desert-Max”, and Figs. 6c and 6f are for the “S&F Maritime” model. The coefficient $\varepsilon$ is basically dependent on the OA of the instrument as well as the aerosol type (size distribution and refractive index of the aerosol).

As expected, the wavelength dependency of the coefficient is influenced by the size distribution pattern, with the fine-particle-rich distribution such as the “S&F Urban” model showing a weak dependency. In Fig. 6b (“Desert-Max”), the lines have no abnormal fluctuations around the 500 nm wavelength because the effect of the discontinuous SSA at 500 nm as shown in Fig. 3b disappears when SSA is taken as a variable.

The relationship between the coefficient $\varepsilon$ and the AE $\alpha$ is depicted in Fig. 7. In the simulation, the AE is defined by using four wavelengths of 400, 500, 675, and 870 nm. In general, a smaller $\alpha$ can give a larger $\varepsilon$ because of rich coarse-mode particles. The figure follows this trend, except for models of “BD-C” and “BD-C1”, which have been proposed by Braslau and Dave (1973). The AOTs of these two models have a unique dependence on the wavelength, with peaks
shown at 500 nm. The small coefficients $\varepsilon_s$ mean that smaller AOTs at wavelengths shorter than 500 nm can produce less forward scattering. In addition, the AE values seem to be smaller apparently because of the definition.

From Table 3 and Fig. 6, the percentage error of the optical thickness estimation can be approximately found using $\Delta \tau \approx -\varepsilon \omega \tau_{aer}$. Also from these points, it is important to determine the appropriate OA when a new instrument for DNI observation is designed.

4. Summary

Error analysis in sun photometry has been performed with measurements of direct normal irradiance (DNI), including a forward scattering part as well as the true DNI. The error to be estimated in this analysis is discussed based on the contribution of the forward scattering to the optical thickness by assessing the forward scattering ratio $\gamma_{fwd}$ to the true DNI $I_T$, as defined by $I_{obs} = I(1 + \gamma_{fwd})$.

The forward scattering effect can cause no erroneous calibration constant as estimated by using the Langley plot technique, despite the underestimate of the apparent optical thickness. However, when calibration is performed by comparing a sample instrument with a reference one, there would be a calibration error if both instruments have different OAs.

In the analysis, the amount of forward scattering is simulated by using the radiative transfer code (SMARTS 2.9.5) with three typical aerosol types: “S&F Urban”, “Desert-Max”, and “S&F Maritime” at three OAs of instrument. The forward scattering ratio is approximately proportional to the product of the aerosol scattering optical thickness and the relative AM ($\gamma_{fwd} \approx \varepsilon \omega \tau_{aer}$). The coefficient $\varepsilon$ is a proportional constant which is dependent on the OA of the instrument and the optical characteristics of aerosols. The error is approximately expressed by $\Delta \tau \approx -\varepsilon \omega \tau_{aer}$.

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