Retrieval of aerosol single scattering albedo and polarized phase function from polarized sun-photometer measurements for Zanjan atmosphere

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Abstract

Aerosol optical depth, Ångström exponent, single scattering albedo, and polarized phase function have been retrieved from polarized sun-photometer measurements for atmosphere of Zanjan (36.70° N, 48.51° E, and 1800 m a.m.s.l.) from January 2010 to December 2012. The results show that the maximum value of aerosol polarized phase function as well as the polarized phase function retrieved for a specific scattering angle (i.e. 60°), are strongly correlated with the Ångström exponent. The latter one has a meaningful variations respect to the changes in the complex refractive index of the atmospheric aerosols. Furthermore the polarized phase function shows a moderate negative correlation respect to atmospheric aerosol optical depth and single scattering albedo. Therefore the polarized phase function can be regarded as a key parameter to characterize the atmospheric particles.

1 Introduction

Physical and optical properties of the atmospheric aerosols are from the major uncertainties in the global climate changes (Solomon et al., 2007). In order to reduce the lack of extensive and reliable information about aerosols and their impact on atmosphere, they have been widely investigated by ground-based measurements and satellite remote sensing suits (Heintzenberg et al., 1997; Kaufman et al., 2002). Ground-based measurements are ideal for reliable and continuous derivation of aerosol optical and physical properties due to negligible effects of surface background on the measurements (Holben et al., 1998; Dubovik et al., 2002).

Iran is located within the so-called Earth’s dust belt. Many cities in west, east, south, and central part of this country had been subjected to dust events of different strength, especially during the recent years. Previous observations show that the Tigris–Euphrates Basin in west, Arabian Peninsula in south and southwest, and the arid region between the Caspian and Aral seas in north are the main external
sources for the observed dust activities in this region (Prospero et al., 2002; Leon and Legrand, 2003; Goudie et al., 2006; Bayat et al., 2011; Abdi et al., 2011, 2012; Sabetghadam et al., 2012; Masoumi et al., 2013). There are also some minor active dust sources inside the Iran plateau (Abdi et al., 2011, 2012; Masoumi et al., 2013). Zanjan, a city in Northwest Iran, is located in a mountainous region at 36.70° N, 48.51° E, and 1800 m a.m.s.l. Zanjan meteorological office data shows that the average of sunny times for this city is more than 7 h per day (Samimi et al., 1997). Considering the geographical location as well as the climatological conditions and lack of measurement data for the region, ground based measurements in this city provide valuable information on the dust activities.

In our previous works, different optical and physical parameters of atmospheric aerosols including; aerosol optical depth ($\tau_a$), Ångström exponent ($\alpha$), volume size distribution, complex refractive index, and single scattering albedo ($\omega_0$) have been studied during 2006 to 2010 (Bayat et al., 2011; Masoumi et al., 2013). In this work, both non-polarimetric and polarimetric measurements of a CIMEL CE318-2 sun-photometer (SPM) at 870 nm have been used to retrieve $\omega_0$ and polarized phase function ($q_a(\Theta)$) of the aerosols. These parameters have been retrieved from recordings of sun-scattered radiance measurements at 870 nm in the Solar Principal Plane (SPP), during January 2010 to December 2012. The SPP is a sweep of sky in a plane that includes the sun and the zenith directions. Polarized sky radiance strongly depends on the presence of aerosols in the atmosphere and it can be monitored by looking through $q_a(\Theta)$ (Vermeulen et al., 2000). To characterize the atmospheric aerosols, we looked to the correlation between $q_a(\Theta)$ and $\alpha$ as well as $q_a(\Theta)$ and $\tau_a$. Also the correlation between $q_a(\Theta)$ and $\omega_0$ has been considered. It should be added that taking into account the aerosol polarized phase function inside the inversion algorithms that usually are used for retrieving the physical properties of the aerosols (i.e. aerosol volume size distribution and complex refractive index), increases the accuracy of calculations and outputs of the algorithms (Li et al., 2006).
The rest of manuscript is organized as follows: in Sect. 2, the retrieval algorithm of aerosol parameters has been explained. The measurement procedure and the obtained results are appeared in Sect. 3. Section 4 is a discussion over the obtained results.

2 Method

Propagation of solar radiation throughout the atmosphere can be modelled by solving the vector radiative transfer equation (VRTE) for a multilayer plane parallel atmosphere, where each layer is specified by its optical depth, single scattering albedo, and scattering matrix (Chandrasekhar, 1950; Zdunkowski et al., 2007). For a random distribution of spherical particles, the stokes vector of scattered light can be obtained by transferring its components for the incident light by means of:

$$
\begin{pmatrix}
I_s \\
Q_s \\
U_s \\
V_s
\end{pmatrix} = \frac{\Omega_{\text{eff}}}{4\pi} \begin{pmatrix}
P_{11}(\Theta) & P_{12}(\Theta) & 0 & 0 \\
0 & P_{12}(\Theta) & 0 & 0 \\
0 & 0 & P_{33}(\Theta) & P_{34}(\Theta) \\
0 & 0 & -P_{34}(\Theta) & P_{44}(\Theta)
\end{pmatrix} \begin{pmatrix}
I_0 \\
0 \\
0 \\
0
\end{pmatrix},
$$

where $\Theta$ is the scattering angle, $\Omega_{\text{eff}}$ indicates the effective solid angle associated with the scattering angle and can be obtained by normalization of the phase function, $p_a(\Theta)$ [i.e. the $P_{11}(\Theta)$ term] (Van de Hulst, 1980; Zdunkowski et al., 2007). Here, the aerosol polarized phase function, $q_a(\Theta)$, stands for the $P_{12}(\Theta)$ term. $I$, $Q$, $U$, and $V$ are the stokes parameters, and the subscript “s” refers to the scattered light. Since the incident solar light at the top of the atmosphere is unpolarized, its Stokes parameters would be represented by $[I_0, 0, 0, 0]$. On the ground level the total sky radiance and polarized sky radiance ($L$ and $L_p$) respectively equals to $I_s$ and $Q_s$, that can be extracted from the total and polarized measurements of the SPM in the SPP mode (Vermeulen et al., 2000; Li et al., 2007, 2009).
The total and polarized sky radiance in the SPP measurement mode have been estimated by solving the VRTE by using the successive order of scattering method (Siewert, 1982; Deuzé et al., 1989; Dubovik et al., 2000; Lenoble et al., 2007; Zdunkowski et al., 2007). Table 1 shows the required parameters that should be used in VRTE to estimate the $L$ and $L_p$. Also, the corresponding measurement or retrieval technique for each parameter has been presented in Table 1.

Using the obtained $L$ and $L_p$ one may retrieve $ω_0$, $p_a(Ω)$, and $q_a(Ω)$ (Devaux et al., 1998; Vermeulen et al., 2000). For simplicity from now on we remove the argument $Ω$ and write $p_a(Ω)$, and $q_a(Ω)$ just as $p_a$, and $q_a$. In this method the contribution of ground reflectance, molecular scattering, and aerosol multiple scattering have been eliminated from the measurements to retrieve the single scattering properties of the atmospheric aerosols (Vermeulen et al., 2000). Since the ratio of (single scattering)/(total scattering) of the sky radiance is nearly the same for measurements and calculations, the relationship between the actual and estimated (marked with a superscript *) sky radiance is given by

$$\frac{ω_0}{ω_0^*} p_a = \frac{L - (L^* - L_{0}^*)}{L_{0}^*} p_a^* + \frac{L - L^*}{L_{0}^*} τ_m \frac{p_m}{ω_0^* p_a^*},$$

where $L$ is the measured, and $L^*$ the estimated total sky radiance. $L_{0}^*$, $p_a^*$, $p_m$, and $τ_m$ are the estimated sky radiance in the absence of ground reflection, the estimated aerosol phase function, the molecular phase function, and the molecular optical depth respectively (Vermeulen et al., 2000). Considering the normalization condition for $p_a$, i.e.

$$\pi \int_0^\pi ω_0 p_a \sin Θ dΘ = 2ω_0,$$
and Eq. (2), will lead to

$$\frac{2 \omega_0}{\omega_0^*} = \int_0^\pi \left( \frac{L - (L^* - L_0^*)}{L^*_0} \right) p_a^* + \frac{L - L^*}{L^*_0} \frac{\tau_m}{\omega_0^* \omega_a} p_m^* \sin \Theta d \Theta,$$

(4)

where $\Theta$ is the scattering angle. The right-hand side of Eq. (4) has been calculated for $\omega_0^* = 0.6, 0.7, 0.8, 0.9$, and $1.0$, then an interpolation has been applied to obtained values to converge the value of the integral to 2, that leads to $\omega_0^* = \omega_0$ in the left hand side. Replacing the retrieved value of $\omega_0$ in Eq. (2), the measured aerosol phase function can be retrieved as

$$p_a = L - \frac{L^*(\omega_0) - L_0^*(\omega_0)}{L_0^*(\omega_0)} p_a^* + \frac{L - L^*(\omega_0)}{L_0^*(\omega_0)} \frac{\tau_m}{\omega_0 \omega_a} p_m.$$  

(5)

In the same way $q_a$ can be written as

$$q_a = \frac{L_p}{L_p^*(\omega_0)} q_a^* + \frac{L_p - L_p^*(\omega_0)}{L_p^*(\omega_0)} \frac{\tau_m}{\omega_0 \omega_a} q_m,$$

(6)

where $q_a^*$ is the estimated polarized phase function, and $q_m$ is the molecular polarized phase function (Vermeulen et al., 2000). Already it has been shown that for a calibrated CIMEL SPM the accuracy on $\tau_a(870$ nm) is $\pm 0.01$, and the estimated total error of the retrieved $\omega_0$ at 870 nm is about $\pm 0.05$. The accuracy of $q_a$ at 870 nm when $20^\circ < \Theta < 120^\circ$ is about 10% (Holben et al., 1998; Devaux et al., 1998; Vermeulen et al., 2000; Li et al., 2006).

During the retrieval of the above mentioned parameters, most of the cloud contaminated data has been eliminated via using the Aerosol Robotic Network (AERONET) cloud screening algorithm (Smirnov et al., 2000). After applying the screening algorithm, still some contaminations were over the data due to existence of inhomogeneous scattered clouds. These have been identified and removed by fitting a robust locally weighted regression to the radiance measurements in the SPP mode (Li et al., 2004). After applying the above procedure, totally 305 measurements have been selected.
3 Measurements and results

In this work, we have investigated the data recorded by a polarized SPM (CIMEL CE318-2) during a 26-month period, as mentioned in Introduction section. The SPM is registered as IASBS on the AERONET and has been calibrated under protocols of the network for the mentioned period. It should be added, during 9 October 2010 to 2 March 2011, and 18 January 2012 to 3 August 2012, the SPM has been sent for calibration. \( \tau_a \) at four wavelengths (440, 675, 870, and 1020 nm) and \( \alpha \) (calculated for \( \tau_a \) at 440, 675, and 870 nm) have been retrieved from the sun mode recorded data (Holben et al., 1998; Toledano et al., 2007; Bayat et al., 2011). Total and polarized sky radiance at 870 nm have been obtained from the SPP recordings to retrieve the \( \omega_0 \) and \( q_a \) (Devaux et al., 1998; Vermeulen et al., 2000).

Figure 1a–d shows the temporal variations of the retrieved \( \tau_a(870\,\text{nm}) \), \( \alpha \), \( q_a(\max) \), and \( \omega_0 \) for the atmosphere of Zanjan and Table 2 includes their minimum, maximum, and mean values for the measurement period. Here \( q_a(\max) \) stands for the maximum value of \( q_a \). Figure 1b, d and Table 2 illustrate that both absorptive fine aerosols (smaller \( \omega_0 \) and \( \alpha > 0.7 \)) and non-absorptive coarse ones (larger \( \omega_0 \) and \( \alpha < 0.7 \)) are presented in the atmosphere of Zanjan with a larger share of the latter ones. Such behavior is due to dominant existence of dust particles especially in late spring and early summer while almost a constant background contamination of anthropogenic aerosols exists in the atmosphere. This is quite in agreement with our previous results that indicate dust is the main contaminant of the atmosphere in this region (Bayat et al., 2011; Masoumi et al., 2013). Figure 1d includes \( \omega_0 \) values from AERONET that have been retrieved from the almucantar sky recordings at 870 nm for IASBS site as well as its values that have been obtained from SPP measurement recordings (our technique). The accuracy of retrieved \( \omega_0 \) from AERONET is \( \sim 0.03 \) to \( \sim 0.07 \) (Dubovik et al., 2002). The retrieved

\[1 \text{The calibrations have been carried in the Photon Group, Laboratoire d’Optique Atmosphérique (LOA) – UFR de Physique Université des Sciences et Technologies de Lille (USTL) – CNRS.}\]
ω₀ accuracy from the both mentioned algorithms depend on τₐ, i.e. the larger τₐ the better accuracy. Referring to Fig. 1d, the difference between the results obtained from the two mentioned techniques is less than 0.05 for most of the cases. The differences also can be due to the time difference of about 10 min between these two measurement modes and also to the different impact of the surface reflectance on their measurement geometries. Referring to Fig. 1b, c, it can be observed, α and qₐ(max) more or less have similar temporal variations. In other words, it can be concluded that qₐ(max) is more sensitive to the aerosol size respect to other parameters, i.e. τₐ and ω₀.

Figure 2 depicts variations of qₐ versus the scattering angle for two measurements with the same τₐ but different α. The larger (smaller) α = 1.49 (α = 0.78) corresponds to the larger (smaller) value of qₐ(max) = 0.22 (qₐ(max) = 0.09).

Figure 2 is an example of such comparisons and other measurements also show similar behaviors. This can be observed in Fig. 3 where there is a strong positive correlation between qₐ(max) and α. The color bar in Fig. 3 corresponds to τₐ values in logarithmic scale. As in our previous work (Masoumi et al., 2013) a negative correlation between α and τₐ can be observed in Fig. 3.

In Fig. 4, variations of qₐ at different scattering angles have been compared for atmospheres with the same α but different τₐ. These results illustrate a moderate influence of variations of τₐ on qₐ. Figure 5 depicts the variations of qₐ(max) at different values of τₐ. Colors in this figure are mapped to different values of α in linear scales. By looking to Fig. 5, one can conclude that qₐ is not so much sensitive respect to τₐ and has a moderate negative correlation with its variations.

4 Discussion

Our previous works, showed that dust and anthropogenic aerosols are the most dominant contaminant particles in the Zanjan atmosphere (Bayat et al., 2011; Masoumi et al., 2013). Considering the positive and negative correlations of qₐ(max) with α and τₐ, respectively (Figs. 3 and 5), one may conclude, during dust activities (increase
of aerosol size and $\tau_a$), $q_a(\text{max})$ considerably is decreasing. A comparison between Figs. 3 and 5 shows that $q_a(\text{max})$ is more sensitive to $\alpha$ than $\tau_a$ for this region. As mentioned before, $\omega_0$ is another crucial parameter in characterization of atmospheric aerosols. It mostly depends on the particles composition and size distribution (Dubovik et al., 2002). Figure 6 shows the correlation between $q_a(\text{max})$ and $\omega_0$, where colors indicate for variations of $\tau_a$. Each data point has been specified by a solid circle whose diameter is mapped to $\alpha^{-1}$ as a qualitative measure of the particle size. For $\tau_a > 0.30$, $q_a(\text{max})$ is almost constant ($\sim 0.05$). Also, a moderate negative correlation between $q_a(\text{max})$ and $\omega_0$ can be observed, when $\tau_a$ is less than 0.30. As a result, the smaller and absorptive aerosols (smaller value of $\omega_0$ when $\tau_a < 0.30$) in the atmosphere cause the larger polarized phase function, and vice versa. Therefore, the polarized phase function can be chosen as a good candidate to characterize the atmospheric particles. To check this, in Fig. 7, $q_a(60^\circ)$ has been plotted versus $\alpha$ for three different refractive indices ($m_1 = 1.40 - i0.010$, $m_2 = 1.45 - i0.005$, and $m_3 = 1.55 - i0.001$), based on the Mie scattering theory for spherical particle. The plots have been overlaid on the retrieved values $q_a(60^\circ)$ for the measurements in the IASBS site. The chosen refractive indices $m_1$, $m_2$, and $m_3$, are almost corresponding to anthropogenic aerosols (Dubovik et al., 2002), Southeast Asian aerosols (AERONET network, Chen-Kung site in Taiwan), and dust (Dubovik et al., 2002) respectively. Figure 7 shows, the events with lower values of $\alpha$ are almost close to the curve for $m_3$ (dust) but as $\alpha$ increases the data get more close to $m_2$ and $m_1$ curves that are corresponding to the aerosols resulted from incomplete fuel burning and anthropogenic aerosols respectively (Dubovik et al., 2002; Cattrall et al., 2005; Kokhanovsky, 2008). The figure also shows that for $\alpha < 0.4$, the data is not well fitted to the curves. We guess this should be due to the spherical shape assumption for the particles in retrieving $q_a$. Finally we would like to conclude, the polarized phase function is a powerful tool for characterizing the atmospheric aerosols and can provide valuable information on their optical and physical properties.
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References


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Table 1. The required parameters for solving VRTE to calculate the $L$ and $L_p$.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Measurement or retrieval technique</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_a$(870 nm)</td>
<td>Sun mode recordings</td>
<td>Holben et al. (1998)</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Retrieved from $\tau_a$ at 440, 675, 870 nm</td>
<td>Toledano et al. (2007)</td>
</tr>
<tr>
<td>$\tau_m$</td>
<td>Surface pressure recorded data</td>
<td>Bodhaine et al. (1999)</td>
</tr>
<tr>
<td></td>
<td>From on site weather station (CIMEL, Model: ENERCO 408p)</td>
<td></td>
</tr>
<tr>
<td>Ground surface reflectance</td>
<td>MODIS surface reflectance product</td>
<td>Lucht et al. (2000)</td>
</tr>
<tr>
<td>Molecular scattering matrix</td>
<td>Rayleigh scattering theory</td>
<td>Liou (2002)</td>
</tr>
<tr>
<td>Aerosol scattering matrix</td>
<td>Mie scattering theory</td>
<td>Liou (2002)</td>
</tr>
<tr>
<td>$\omega_0$</td>
<td>Mie scattering theory</td>
<td>Liou (2002)</td>
</tr>
</tbody>
</table>
Table 2. Minimum, maximum, and mean values of $\tau_a$, $\alpha$, $q_a$(max), and $\omega_0$ for 305 selected data, January 2010 to December 2012, IASBS site.

<table>
<thead>
<tr>
<th></th>
<th>Min</th>
<th>Max</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_a$</td>
<td>0.02</td>
<td>0.61</td>
<td>0.15</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>0.07</td>
<td>1.79</td>
<td>0.85</td>
</tr>
<tr>
<td>$q_a$(max)</td>
<td>0.04</td>
<td>0.32</td>
<td>0.14</td>
</tr>
<tr>
<td>$\omega_0$</td>
<td>0.64</td>
<td>0.99</td>
<td>0.90</td>
</tr>
</tbody>
</table>
Fig. 1. (a) $\tau_a(870 \text{ nm})$, (b) $\alpha$, (c) $q_a(\text{max})$, and (d) $\omega_0$ retrieved from SPP mode (our results, solid black circles) and Almucantar mode (AERONET results, empty red squares) measurements versus day of year, January 2010 to December 2012, IASBS site.
Fig. 2. Retrieved $q_a$ at 870 nm versus the scattering angle, in the atmosphere of Zanjan for two measurements with same $\tau_a$ and different $\alpha$, IASBS site.
**Fig. 3.** Strong positive correlation between $q_a(\text{max})$ at 870 nm and $\alpha$, colors are mapped to $\tau_a$ in logarithmic scale, January 2010 to December 2012, IASBS site.
Fig. 4. Retrieved $q_a$ at 870 nm in the atmosphere of Zanjan for two measurements with same $\alpha$ and different $\tau_a$, IASBS site.
Fig. 5. Variations of $q_a(\text{max})$ versus $\tau_a(870 \text{ nm})$ in logarithmic scale, colors are mapped to $\alpha$ in linear scale, January 2010 to December 2012, IASBS site.
Fig. 6. Correlation between $q_a(\text{max})$ and $\omega_0$ at 870 nm, colors are mapped to different values of $\tau_a$. Diameter of each data point corresponds to $\alpha^{-1}$. 
Fig. 7. $q_a(60^\circ)$ versus $\alpha$, for 305 retrieved data points (colored circles), lines calculated for three different presumed refractive indices based on Mie scattering theory.