Assessment of error in aerosol optical depth measured by AERONET due to aerosol forward scattering

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Abstract

We present an analysis of the effect of aerosol forward scattering on the accuracy of aerosol optical depth (AOD) measured by CIMEL Sun photometers. The effect is quantified in terms of AOD and solar zenith angle using radiative transfer modeling. The analysis is based on aerosol size distributions derived from multi-year climatologies of AERONET aerosol retrievals. The study shows that the modeled error is lower than AOD calibration uncertainty (0.01) for the vast majority of AERONET level 2 observations, ~99.53%. Only ~0.47% of the AERONET database corresponding mostly to dust aerosol with high AOD and low solar elevations has larger biases. We also show that observations with extreme reductions in direct solar irradiance do not contribute to level 2 AOD due to low Sun photometer digital counts below a quality control cutoff threshold.

1. Introduction

Ground based observations are an important component of global aerosol monitoring providing both validation datasets for satellite AOD retrievals and characterization of temporal variability of aerosol properties at different parts of the globe [*Holben et al*., 2001]. The Aerosol Robotic Network (AERONET) [*Holben et al*., 1998] provides the largest AOD dataset resulting from multi-year observations at more than 500 locations all over the world. The observations of transmitted solar radiation at 340, 380, 440, 500, 675, 870, 940 and 1020 nm (nominal wavelengths; extended wavelength versions additionally have 1640 nm) are performed by CIMEL Sun photometers which have field-of-view (FOV) of 1.2°.

The uncertainty in AOD measurements from CIMEL field instruments, due primarily to calibration uncertainty, was estimated in *Eck et al*. [1999] to be ~0.01 in the visible and near-IR, increasing to ~0.02 in the ultraviolet (340 and 380 nm). *Eck et al*. [1999] also estimated the relative AOD error due to aerosol forward scattering to be ~ 0.7% for coarse mode only dust aerosol with effective radius 1.75 μm. This estimate gives absolute bias smaller than 0.01 for AOD lower than ~ 1.5.

Recent research [*Zhao et al*., 2012; Ge et al., 2011] emphasized the importance of aerosol forward scattering effects in situations with high aerosol loading and large solar zenith angles (SZA). In particular *Zhao et al*. [2012] showed that transmitted solar radiation decreases faster than aerosol scattering for increasing AOD and SZA thus resulting in larger AOD error. Using radiative transfer modeling combined with Junge aerosol size distributions (ASD) *Zhao et al*., [2012] asserted that for coarse mode dust AOD biases can be as large as ~4% at 440 nm for AOD of 3.5 and SZA 70°. To compute this number, the quantities reported in *Zhao et al*., [2012] need to be multiplied by cosine of SZA before calculating the relative error for AOD - see

Section 2 for details. Much larger uncertainties are reported for 80° SZA. The errors estimated in *Zhao et al*., [2012] are the largest for 1.2° FOV reported so far. For example, analysis by *Ge et al*., [2011] suggested that "the dust aerosol forward scattering may not significantly affect the accuracy of CIMEL retrieved AOD". One of the possible reasons for large reported errors could be a result of employing the Junge ASD, which is a rather crude approximation to the real size distributions.

The effect of aerosol forward scattering for 1.2° FOV was the subject of several research studies [*Box and Deepak*, 1979; *Russell et al*., 2004; *Ge et al*., 2011]. However no estimations were reported for very large AOD and SZA. For example, the approach used in *Russell et al*., [2004] is valid for maximum slant AOD of 6.0, which corresponds to AOD ~ 1.5 for SZA of 75°. *Ge at al*., [2011] performed extensive simulations as a function of AOD and SZA but for the 3.3° FOV only. In addition, the results of *Zhao et al*., [2012] can create a misconception about the accuracy of AOD measured by AERONET; therefore a realistic assessment of the forward scattering effect for the AERONET data base is important. In this paper we present results of aerosol forward scattering effect modeling for wide ranges of both AOD and SZA using both Junge distributions as well as realistic ASDs based on AERONET aerosol retrievals. We also assess how cases with large AOD and low solar elevations are represented in the variability of AOD observed by AERONET. Our analysis is primarily focused on coarse mode dust aerosols which exhibit a strong forward scattering pattern. A less detailed consideration for fine mode aerosols is also presented.

2 Approach

In this study radiative transfer modeling of aerosol forward scattering effects is performed similar to *Zhao et al*., [2012] for AOD varying from 0.1 to 3.5 and SZA in the range from 40° to 75° and four spectral channels 440, 675, 870, and 1020 nm. Integration limits for the ASD particle radius are 0.05 and 15 μm as in the AERONET aerosol retrieval code [*Dubovik and King*, 2000]. Radiative transfer calculations were performed using the code of *Nakajima and Tanaka*, [1988]. The aerosol complex refractive index used in calculations was 1.5-0.003i (wavelength independent) for the dust cases analysis. Non-spherical dust aerosol calculations were performed using a model of randomly oriented spheroids with fixed shape distribution [*Dubovik et al*., 2002; *Dubovik et al*., 2006].

Three factors determine error in AOD due to aerosol forward scattering effects: (1) irradiance scattered into the Sun photometer field of view R_s, (2) direct transmitted irradiance R_d and (3) cosine of SZA μ_0. These parameters are combined into the following equation for AOD retrieval error which is derived from the Bouguer law

$$\Delta\tau = \mu_0 \ln(1+R_s/R_d)\ . \qquad (1)$$

Equation (1) is further used for estimating AOD error in this study. For small R_s/R_d the above equation becomes

$$\Delta\tau \approx \mu_0\, R_s/R_d\ . \qquad (2)$$

Equation (2) shows that AOD bias is directly proportional to the ratio R_s/R_d. The values of this ratio are reported in *Zhao et al*., [2012] as absolute AOD errors thus differing from the definition of Equation (2) by cosine of SZA.

3 Aerosol size distribution

The Junge ASD is a power law distribution sometimes used to approximate real ASDs [*McMurry*, 2000]. Although it doesn't capture the detailed ASD shape, the Junge distribution can be considered as an average envelope curve of more realistic multi-modal ASDs [*Davies*, 1974]. At the same time as shown by *Tomasi et al.,* [1983], in some cases, the Junge distribution can produce unrealistic ASD shapes. In our analysis, Junge ASD for α=0.2 is used following *Zhao et al*. [2012] and employing the following relationship between Angstrom exponent (α) and exponent of the Junge distribution ν

$$\alpha = \nu - 3. \tag{3}$$

Due to the approximate nature of Equation (3) [*Tomasi et al.,* 1983], the Angstrom exponent calculated directly from computed spectral AOD is different from 0.2 and equals ~0.3.

It is noted that in situ measurements of dust size distributions have shown good agreement with AERONET retrieved ASDs [*Reid et al*., 2003, *Reid et al*., 2008, *Johnson and Osborne*, 2011]. Therefore, ASDs based on multi-year (2000-2011) climatologies of AERONET aerosol retrievals for selected dust dominated sites were used in modeling of the FOV effect along with the Junge ASD. The climatologies were developed for observations with 440 nm AOD ranging from 0.5 to 0.6.

Figure 1 shows a comparison of the Junge ASD with AERONET ASDs for dust dominated observations. All distributions correspond to the same AOD at 440 nm. Figure 1 shows that the Junge ASD for particles larger than ~ 3 μm radius is unrealistic and significantly overestimates the contribution of large aerosols. For example, despite close Angstrom exponents, the Junge and Solar Village ASDs have very different total effective radii of 2.152 and 0.8 μm (3.74 and 2.3 μm coarse mode) respectively suggesting different aureole patterns due to the dependence of forward scattering intensity on the effective radius. The above comparison suggests that using AERONET ASDs instead of Junge in modeling of aerosol forward scattering could result in lower error in AOD than that reported by *Zhao et al.*, [2012].

4 Results.

Figure 2 shows the dependence of Δτ modeled using both Junge and AERONET based ASDs for the 440 nm channel and four SZAs. Using the AERONET AOD uncertainty of 0.01 as a baseline for comparison, Figure 2 shows that values of the Junge based estimated error are lower than 0.01 for AOD smaller than ~0.4, regardless of SZA. At the same time AERONET based estimated biases are lower than 0.01 for AOD smaller than ~1.2 which gives three times greater range. Despite significant differences in Angstrom exponent, all three AERONET based ASDs produce similar modeled errors due to close values of total effective radii: 0.782, 0.798, and 0.60 μm (1.92, 2.3, and 2.6 μm for coarse mode) for Cape Verde, Solar Village, and Kanpur ASDs respectively. Figures 2c and 2d show that Junge and AERONET based estimates converge to each other for high values of AOD and SZA. This is where the effect of reduction in transmitted solar radiation starts to dominate and diminish the effect of ASD. Red lines on Figures 2c and 2d represent the threshold values of AOD above which the number of digital counts for Sun photometer measurements is lower than the AERONET Level 1.5 and Level 2 cut-off value, which was implemented in the Version 2 data set (Nov 2006) for quality control purposes. For AOD to be raised to Level 1.5 and Level 2, the instrument measured raw count must be larger than 10 at 440 nm. If the 440 nm count is < 10 then all channels are excluded from both Level 1.5 and Level 2. The AOD boundary values were estimated to be 1.8 and 2.5 for SZAs 75° and 70° degrees respectively (the low count threshold was not reached for SZAs 40°

and 60°), using the Bouguer law and assuming that the number of counts at the top of the atmosphere is 15000 (a typical value of the extraterrestrial voltage, Vo, for AERONET CIMELs). Thus the low count threshold filters out cases with large SZAs and extremely large AOD values, which according to *Zhao et al.* [2012] exhibit the largest AOD uncertainties.

The spectral dependence of AOD FOV error was also analyzed. Figure 3 presents AOD errors for four different wavelengths over a range of different SZAs for each wavelength, for the Capo Verde ASD. Only modeled AOD errors corresponding to AERONET Levels 1.5 and 2 data are plotted; observations corresponding to the number of digital counts below the low signal threshold are excluded. One can see that $\Delta\tau$ decreases and the AOD value for 0.01 error increases and becomes more SZA dependent as wavelength increases. The spectral dependence of $\Delta\tau$ has a small effect on the values of the Angstrom exponent (440 -870 nm). For example, the bias in α for 440 nm AOD of 2 was estimated to be ~0.01.

In general much smaller contributions to aerosol forward scattering effects from fine mode aerosols is expected [*Kinne et al*., 1997; Ge et al., 2011]. Figure 4, shows results of simulations for 440 nm obtained using ASD based on AERONET aerosol retrievals for the GSFC site (1997-2009; 440 nm AOD ~0.5) and refractive index of 1.4-0.005i. As can be seen, $\Delta\tau$ estimates at 440 nm are smaller than ~0.01 for the majority of solar elevations considered reaching the maximum value of ~0.025 for 60° SZA and AOD of 3.5. For longer wavelengths (not shown) the errors are always lower than 0.01.

The above analysis suggests that for both dust and fine mode aerosols the threshold values of 440 nm AOD below which the FOV bias is lower than the AERONET calibration uncertainty can be defined. For dust aerosols the threshold value is nearly SZA independent and approximately equals to 1.2 while for fine mode aerosols it depends on SZA and can be approximated by

$$T=1.8787 \ln(\mu_0)+4.2895. \tag{4}$$

These threshold values were used to estimate the percentage of observations in the AERONET data base with FOV error larger than 0.01 using the value of Angstrom exponent of 0.75 to separate aerosol size categories of fine versus coarse mode domination [Eck et al., 2010]. The percentage of AOD measurements in the Level 2 data with FOV bias greater than 0.01 was estimated to be ~0.47% (0.46% for dust; 0.01% for fine mode aerosols), meaning that the great majority of AERONET AOD retrievals have FOV error smaller than 0.01.

5 Conclusions

In this paper the error in AOD, estimated from 1.2° FOV Sun photometer observations, due to the aerosol forward scattering effect has been evaluated. Analysis was performed using radiative transfer modeling employing both a Junge ASD and ASDs based on AERONET aerosol retrievals. Using the Junge ASD in radiative transfer modeling resulted in considerable overestimates of modeled AOD error as compared to more realistic AERONET based ASDs which were used in subsequent analysis. The analysis found that 99.53% of the AERONET AOD data have 440 nm bias errors due to FOV effects much lower than the AERONET AOD estimated uncertainty of 0.01. Only ~0.47% of the AERONET Level 1.5 and Level 2 data corresponding mostly to dust aerosol with high AOD and low solar elevations have AOD error larger than 0.01. We also showed that observations with extreme reductions in direct solar irradiance and potentially large AOD errors do not contribute to Level 1.5 and Level 2 AOD due to low Sun photometer digital counts that are below the AERONET threshold. Potentially AOD retrievals with FOV error larger than 0.01 and the signal level above the digital counts threshold can be flagged as diffuse light contaminated. These AOD retrievals could be corrected using radiative transfer modeling for a set of representative ASDs.

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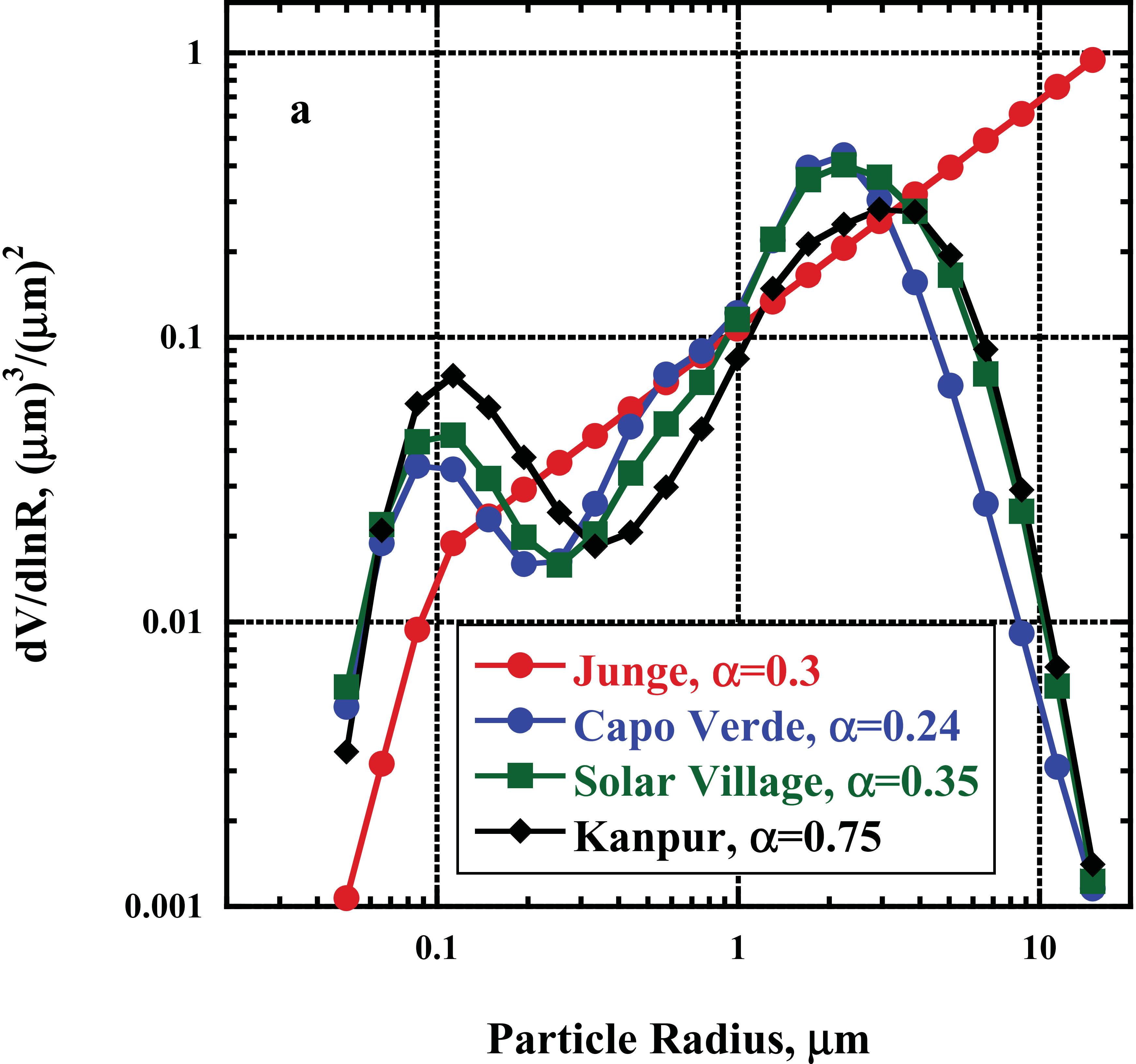
Figure Captions

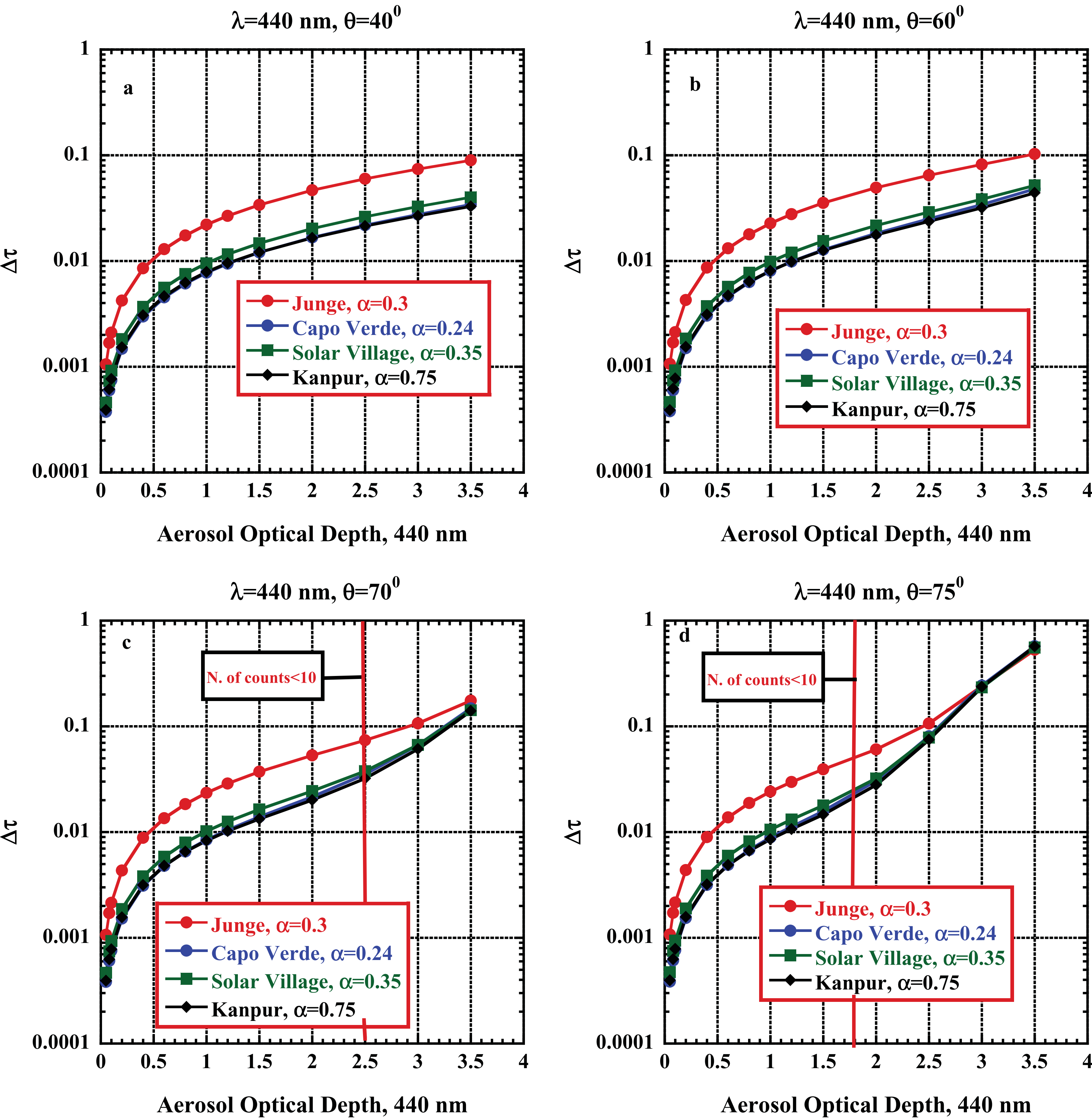
Fig.1 Aerosol size distributions used in FOV error analysis: the Junge ASD with computed Angstrom exponent of 0.3 and ASDs based on aerosol retrievals for three AERONET sites dominated by dust. All ASD's are normalized to have the same AOD at 440 nm.

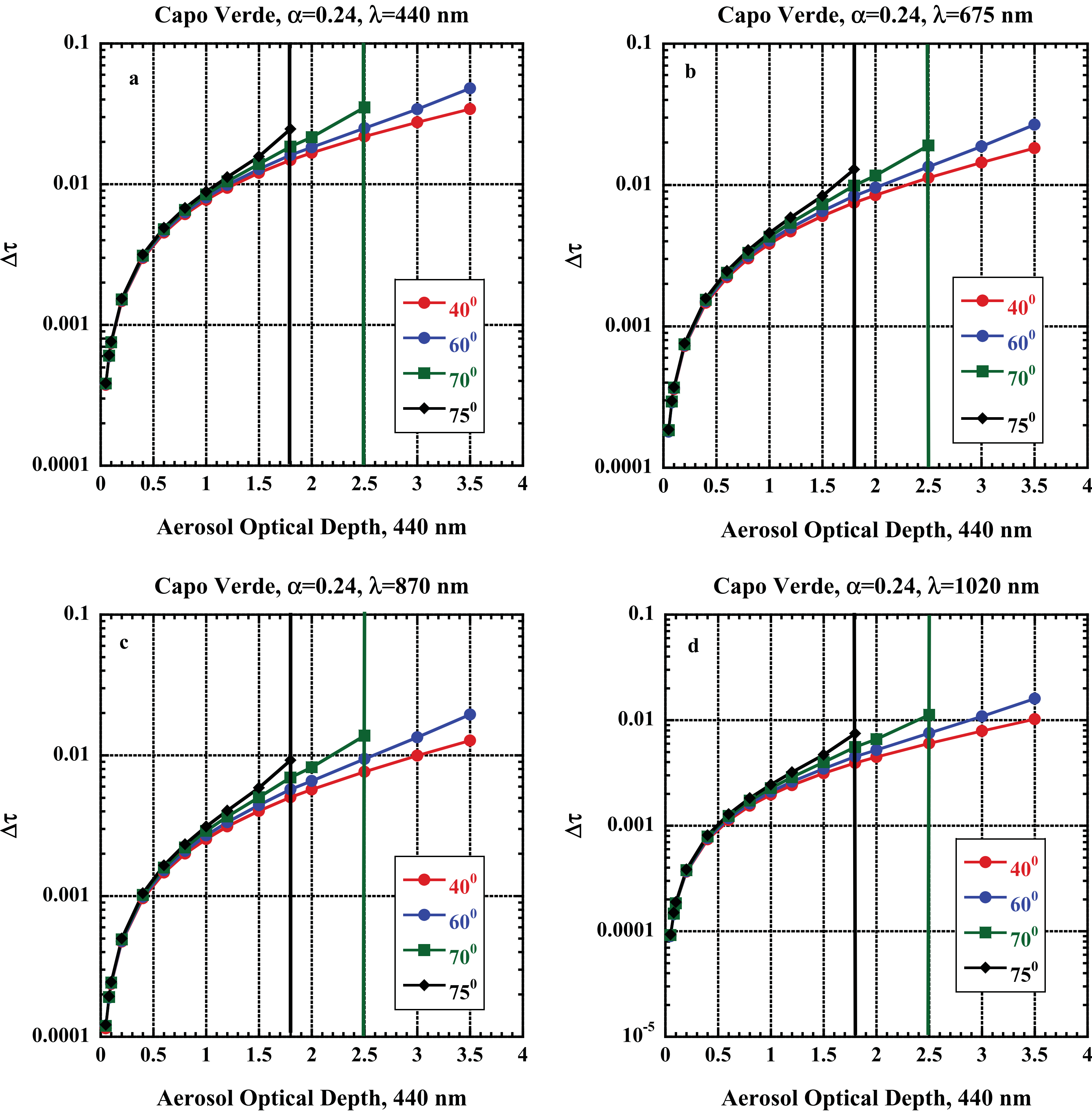
Fig.2 Errors in 440 nm AOD due to diffuse radiation scattered into the Cimel instrument FOV modeled for dust aerosols for four SZAs: a) 40°, b) 60°, c) 70°, and d) 75°. The low count threshold of 10 counts indicated at 70° and 75° was not reached for the 40° and 60° SZA simulations

Fig.3 AOD biases for dust aerosols, utilizing the AERONET Cape Verde site ASD, due to FOV effects for different wavelengths: a) 440 nm, b) 670 nm, c) 870 nm, d) 1020 nm. Only observations corresponding to the number of digital counts above the low signal threshold are shown.

Fig.4 Same as in Fig.3 for 440 nm only, but for fine mode aerosols, utilizing the AERONET GSFC site ASD. For longer wavelengths (not shown) the errors are always lower than 0.01.


a
dV/dlnR, (μm)^3/(μm)^2
1
0.1
0.01
0.001
Particle Radius, μm
0.1
1
10
Junge, α=0.3
Capo Verde, α=0.24
Solar Village, α=0.35
Kanpur, α=0.75


λ=440 nm, θ=40⁰
λ=440 nm, θ=60⁰
λ=440 nm, θ=70⁰
λ=440 nm, θ=75⁰
a
b
c
d
Δτ
1
0.1
0.01
0.001
0.0001
0
0.5
1
1.5
2
2.5
3
3.5
4
Aerosol Optical Depth, 440 nm
Junge, α=0.3
Capo Verde, α=0.24
Solar Village, α=0.35
Kanpur, α=0.75
N. of counts<10

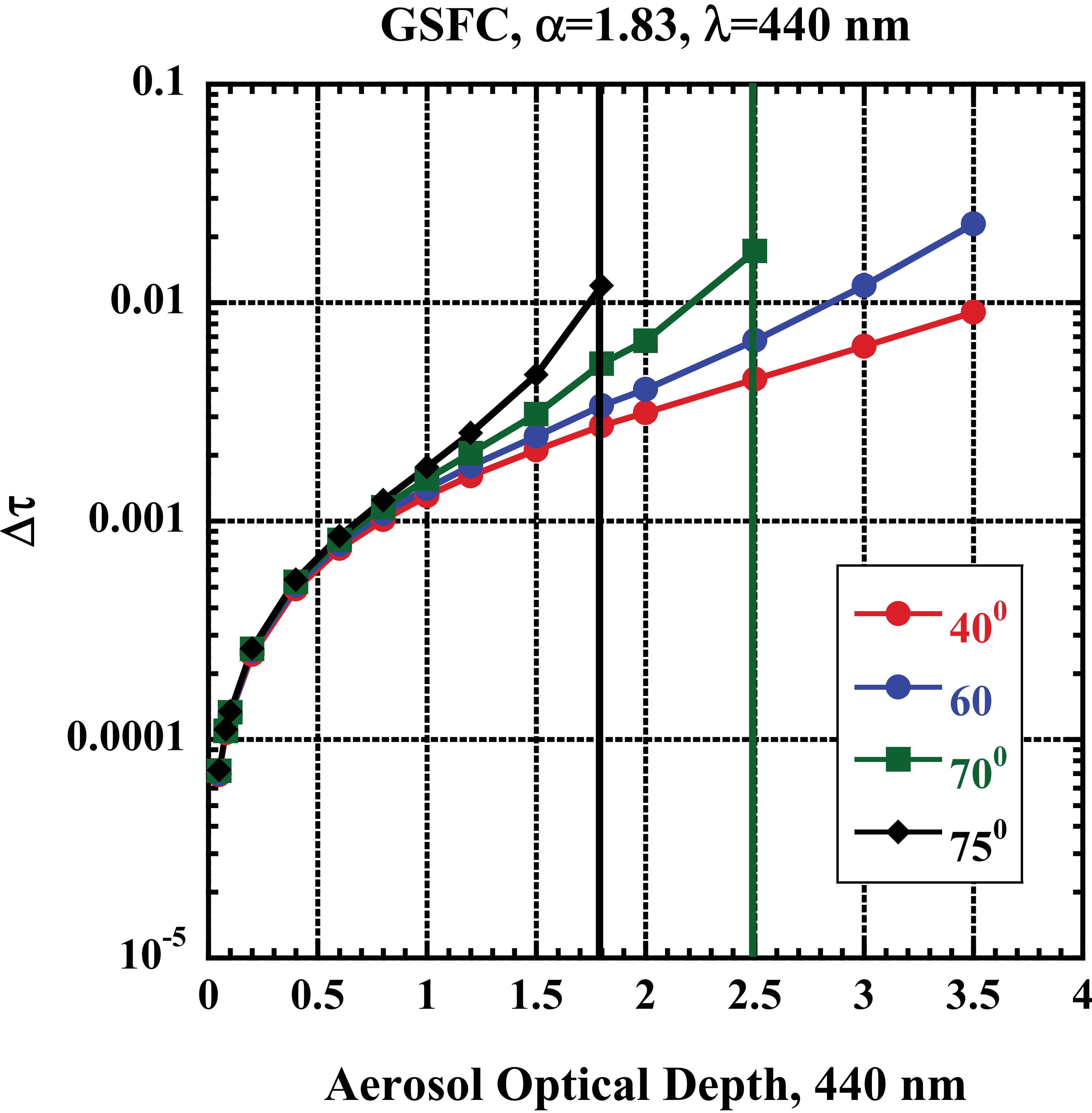


Capo Verde, α=0.24, λ=440 nm

Capo Verde, α=0.24, λ=675 nm

Capo Verde, α=0.24, λ=870 nm

Capo Verde, α=0.24, λ=1020 nm


GSFC, α=1.83, λ=440 nm
Δτ
0.1
0.01
0.001
0.0001
10^-5
0
0.5
1
1.5
2
2.5
3
3.5
4
Aerosol Optical Depth, 440 nm
40^0
60
70^0
75^0