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# A synthesis of single scattering albedo of biomass burning aerosol over southern Africa during SAFARI 2000

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[1] We present a synthesis of single scattering albedo for biomass burning aerosol from the SAFARI 2000 field campaign. Values at 550 nm were derived from three methods: airborne in situ measurements of aerosol scattering and absorption; airborne flux radiometry; and ground-based sun-photometer/radiometer retrievals from AERONET. Collocated comparisons indicate that uncertainties are well understood for all three methods. The new (Version 2) AERONET retrieval gives substantially lower single scattering albedo over bright surfaces, and the comparisons herein represent the first independent check of this retrieval. Combined in situ and AERONET data yield a regional value of  $0.85 \pm 0.02$  (mean and total uncertainty), which we propose is representative of single scattering albedo for the Southern African region during the biomass burning season. This value agrees with the “highly absorbing smoke” model used in MODIS aerosol retrievals, but indicates that many of the AeroCom models overestimate single scattering albedo for this region and season. **Citation:** Leahy, L. V., T. L. Anderson, T. F. Eck, and R. W. Bergstrom (2007), A synthesis of single scattering albedo of biomass burning aerosol over southern Africa during SAFARI 2000, *Geophys. Res. Lett.*, **34**, L12814, doi:10.1029/2007GL029697.

## 1. Introduction

[2] Aerosol direct climate forcing (DCF) describes the modification of Earth’s energy balance due to the direct interaction of anthropogenic aerosols with solar radiation. Estimates using chemical transport/radiative transfer models (CTRTMs) indicate that global-mean DCF is negative, i.e. a cooling effect, and may compensate for a substantial fraction of positive forcing by greenhouse gases [Charlson *et al.*, 1991; Ramaswamy *et al.*, 2001]. Aerosol optical properties controlling DCF are highly variable and not always accurately represented in CTRTMs. For example, Bates *et al.* [2006] found that estimates of DCF for three regions increased in magnitude by an average of 37% when model-derived aerosol optical properties were replaced with measured properties specific to each region.

[3] Mid-visible single scattering albedo,  $\omega$  - the ratio of aerosol light scattering to aerosol light extinction - is among the most important of aerosol optical properties for deter-

mining DCF as well as one of the most challenging to measure [Heintzenberg *et al.*, 1997]. The goal of this study is to constrain the regional-mean value of  $\omega$  for biomass burning aerosol over Southern Africa, suitable for use in CTRTM calculations. We use measurements acquired during the Southern African Regional Science Initiative (SAFARI) 2000 field campaign [Swap *et al.*, 2003], in a two-step process. First, we analyze collocated, independent measurements to provide a robust estimate of measurement uncertainty. We then compare and integrate data from the two techniques that provide regional-scale characterization - airborne in situ measurements from multiple flights and ground-based radiometry from several continuously operating stations.

## 2. Data Sets

[4] Full details on instrumentation, data reduction, and uncertainty derivation are given by Sinha *et al.* [2003, Appendix A], Magi *et al.* [2003], Bergstrom *et al.* [2003], Schmid *et al.* [2003], and Eck *et al.* [2003]. A brief description follows.

### 2.1. In Situ

[5] Aerosol scattering coefficient ( $\sigma_s$ ) and aerosol absorption coefficient ( $\sigma_a$ ) at 550 nm wavelength and low relative humidity (RH) were measured aboard the University of Washington (UW) research aircraft using, respectively, an MS Electron integrating nephelometer and a Radiance Research Particle Soot Absorption Photometer (PSAP). These provide a direct measurement of low-RH  $\omega$  at 550 nm ( $\omega_{550}$ ) as the ratio of  $\sigma_s$  to the aerosol extinction coefficient ( $\sigma_s + \sigma_a$ ). Adjustment to ambient RH was based on humidified nephelometry measurements [Magi and Hobbs, 2003] and an assumption that RH has no effect on  $\sigma_a$ . Because scattering humidification factors were very low (ranging from 1.0 to 1.2), the error associated with this assumption is negligible.

[6] The passing efficiency of the isokinetic aerosol inlet is not well known. The 50% cut-point diameter of an inlet with nearly identical specifications was estimated to be  $4 \mu\text{m}$  [Sinha *et al.*, 2003]. Data from the seven AERONET sites analyzed herein indicate that the ratio of fine to total aerosol extinction (separated at  $1.2 \mu\text{m}$  diameter) was 0.89–0.96. Therefore, we assume that errors associated with poor sampling of large particles are small.

[7] Total uncertainty was estimated by combining instrument noise, precision and systematic uncertainties as described by Anderson *et al.* [2003]. We assign a 25% systematic uncertainty to the PSAP data, somewhat larger than the 20% recommended by Bond *et al.* [1999] to account for unknown accuracy of the internal flow meter. We assign a 10%

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**Table 1.** Derived Parameters Used for Closure Tests

Parameter	Derivation	Instruments Used
<i>Layer</i>		
$\omega_{\text{LAYER}}$	$\frac{\int_{Z_{\min}}^{Z_{\max}} \sigma_s(z) dz}{\int_{Z_{\min}}^{Z_{\max}} \sigma_e(z) dz}$ <p>Retrieval based on the difference in the net flux at the top and bottom of the layer</p>	Airborne in situ <sup>a</sup>  Airborne remote sensing <sup>b,c</sup>
$\tau_{\text{LAYER}}$	$\int_{Z_{\min}}^{Z_{\max}} \sigma_e(z) dz$ <p><math>\tau_{Z_{\max}} - \tau_{Z_{\min}}</math> (<math>\tau</math> from direct solar beam measurements)</p>	Airborne in situ <sup>a</sup>  Airborne remote sensing <sup>c</sup>
<i>Column</i>		
$\omega_{\text{COLUMN}}$	Assumption: $\omega_{\text{COLUMN}} = \omega_{\text{LAYER}}$ Inversion based on $\tau$ and radiances	Airborne in situ <sup>a</sup> Ground-Based Remote Sensing <sup>d</sup>
$\tau_{\text{COLUMN}}$	$\tau_{\text{BELOW,IS}} + \tau_{\text{LAYER,IS}} + \tau_{\text{ALOFT,RS}}$ $\bar{\sigma}_{e,\text{LAYER}} \int_{Z_0}^{Z_{\min}} dz + \int_{Z_{\min}}^{Z_{\max}} \sigma_e(z) dz + \tau_{Z_{\max}}$ <p><math>\tau</math> from direct solar beam measurements</p>	Airborne in situ <sup>a</sup>  Ground-Based Remote Sensing <sup>d</sup>

<sup>a</sup>MS Electron 3-Wavelength Integrating Nephelometer and Particle and Soot Absorption Photometer [Magi et al., 2003].<sup>b</sup>NASA Ames Solar Spectral Flux Radiometer [Bergstrom et al., 2003].<sup>c</sup>NASA Ames Airborne Tracking 14-Channel Sun Photometer [Schmid et al., 2003].<sup>d</sup>Aerosol Robotic Network (AERONET) sun photometer/radiometer [Eck et al., 2003].

systematic uncertainty to the nephelometer, again slightly larger than the literature recommendation of 7% [Anderson et al., 1996].

## 2.2. Remote Sensing Instruments

### 2.2.1. Airborne Remote Sensing

[8] Aerosol optical depth ( $\tau$ ), a measure of aerosol-induced attenuation of the solar beam as it passes through the atmosphere, was measured by the NASA Ames Airborne Tracking Sun-photometer (AATS-14), at 14 wavelengths from 0.345 to 1.557  $\mu\text{m}$ . Cloud screening and other data reduction procedures are described by Schmid et al. [2003]. We used a second order polynomial to interpolate to  $\tau$  at 550 nm ( $\tau_{550}$ ). Uncertainties in  $\tau$  arise from noise, Sun-tracking, airmass computation, corrections for molecular scattering and absorption, and calibration drift.

[9] The NASA Ames Solar Spectral Flux Radiometer (SSFR) measured upwelling and downwelling spectral irradiance (wavelength range 0.300 to 1.700  $\mu\text{m}$ ), at the top and bottom of aerosol layers identified in flight. As

described by Bergstrom et al. [2003], spectral  $\omega$  was estimated by matching modeled to measured net flux difference (net flux at the top of the layer minus that at the bottom). AATS-14 layer  $\tau$  was a model input. Uncertainties in  $\omega$  arise from noise, aircraft pitch and roll, and radiometer calibration. We fitted a second order polynomial to the SSFR data to obtain  $\omega_{550}$  and calculated  $\omega$  uncertainty as the mean of reported uncertainties at 545, 555 and 565 nm.

[10] Both instruments were deployed on the UW aircraft. Data (including uncertainties) were obtained from <http://geo.arc.nasa.gov/sgg/SAFARI/SAFARIdata/SAFARIdata.html>.

### 2.2.2. Ground-Based Remote Sensing

[11] Multiple Aerosol Robotic Network (AERONET) stations were operated during SAFARI 2000 [Eck et al., 2003]. Seven of these sites provided  $\omega$  and  $\tau$  data for this analysis. Column-integrated  $\omega$  is retrieved at four wavelengths (440, 675, 870 and 1020 nm) based on CIMEL Electronique CE-318 Sun-sky sun-photometer/radiometer

**Table 2.** Closure Test: In Situ Versus Remote Sensed Layer Mean<sup>a</sup>  $\omega$  and  $\tau$  at  $\lambda = 550$  nm and Layer Details

Date	$\omega_{\text{LAYER}}$		$\tau_{\text{LAYER}}$		Layer Depth, <sup>d</sup> km	RH, <sup>e</sup> %
	In Situ	SSFR <sup>b</sup>	In Situ	AATS-14 <sup>c</sup>		
24 Aug	0.94 $\pm$ 0.02	0.82 $\pm$ 0.09	0.16 $\pm$ 0.02	0.17 $\pm$ 0.07	2.4/2.7	44 $\pm$ 23
6 Sep	0.84 $\pm$ 0.04	0.87 $\pm$ 0.01	0.71 $\pm$ 0.07	0.77 $\pm$ 0.03	3.3	26 $\pm$ 4

<sup>a</sup>Values are means  $\pm$  uncertainty.<sup>b</sup>SSFR: NASA Ames Solar Spectral Flux Radiometer.<sup>c</sup>AATS-14: NASA Ames Airborne Tracking Sun-Photometer.

<sup>d</sup>On 24 August depth the first value refers to the depth of the layer characterized by the in situ data. It is 281 m shallower in depth than the layer from which SSFR  $\omega$  is calculated (second value given). The difference is due to the uppermost portion of the in situ vertical profile penetrating a layer of clean air. Scattering values fell below the detection limits of the instrument and were not used in calculating the layer mean in situ  $\omega$  value.

<sup>e</sup>RH layer mean  $\pm$  standard deviation.

**Table 3.** Closure Test: In Situ Versus AERONET  $\omega_{\text{COLUMN}}$  and  $\tau_{\text{COLUMN}}$  for  $\lambda = 550 \text{ nm}^a$ 

Date	AERONET Site	$\omega_{\text{COLUMN}}$ In Situ	$\omega_{\text{COLUMN}}$ AERONET	Discrepancy <sup>b,c</sup>	$\tau_{\text{COLUMN}}$ In Situ	$\tau_{\text{COLUMN}}$ AERONET	
						Retrieval time	In situ time
22 Aug	Skukuza	$0.90 \pm 0.02$	$0.90 \pm 0.03$	0.00	$0.29 \pm 0.07$	$0.33 \pm 0.01$	$0.33 \pm 0.01$
3 Sep	Sua Pan	$0.82 \pm 0.04$	$0.87 \pm 0.03$	−0.05	$0.67 \pm 0.07$	$0.64 \pm 0.00$	$0.72 \pm 0.01$
6 Sep	Mongu	$0.84 \pm 0.04$	$0.86 \pm 0.03$	−0.02	$1.00 \pm 0.10$	$1.10 \pm 0.01$	$1.11 \pm 0.01$
6 Sep	Senanga	$0.82 \pm 0.06$	$0.84 \pm 0.03$	−0.02	$1.12 \pm 0.06$	$1.20 \pm 0.01$	$1.16 \pm 0.01$
16 Sep	Etosha Pan	$0.89 \pm 0.04$	$0.86 \pm 0.03$	+0.03	$0.28 \pm 0.09$	$0.31 \pm 0.01$	$0.20 \pm 0.02$

<sup>a</sup>All values are ambient column averaged mean  $\pm$  uncertainty.<sup>b</sup>Discrepancy is calculated as the in situ  $\omega_{\text{COLUMN}}$  − AERONET  $\omega_{\text{COLUMN}}$ .<sup>c</sup>Mean discrepancy is −0.01 and root mean square (RMS) discrepancy is 0.03.

measurements and the *Dubovik and King* [2000] inversion, as recently refined under the Version 2 algorithm. Uncertainty in retrieved  $\omega$  has been estimated to be  $\pm 0.03$  for  $\tau_{440} \geq 0.5$  [Dubovik et al., 2000]. Measured  $\tau$  was interpolated to 550 nm using the  $\tau$  Ångström exponent (wavelength dependence of  $\tau$ ) over the 440–675 nm interval. We estimated errors in  $\tau_{550}$  from uncertainties in  $\tau_{440}$  and  $\tau_{675}$  given by *Eck et al.* [1999]. We fitted a second order polynomial to interpolate to  $\omega_{550}$ . Version 2 Level 2.0 data for SAFARI 2000 were obtained from <http://aeronet.gsfc.nasa.gov>. AERONET Version 2 retrievals of  $\omega$  are expected to be more accurate due to using MODIS derived, seasonally varying, spectral surface albedo and ecosystem-based, bidirectional reflectance distribution function models, as opposed to seasonally invariant green vegetation reflectance spectra with a Lambertian reflectance distribution in Version 1. This change substantially lowers the retrieved  $\omega$  over bright surfaces, such as the Etosha Pan and Sua Pan sites used herein.

### 3. Derived Parameters

[12] Layer ( $\omega_{\text{LAYER}}$  and  $\tau_{\text{LAYER}}$ ) and column parameters ( $\omega_{\text{COLUMN}}$  and  $\tau_{\text{COLUMN}}$ ) were derived for closure test comparisons (Table 1). We compared AERONET  $\omega_{\text{COLUMN}}$  to in situ  $\omega_{\text{LAYER}}$  measurements that characterize only the layer between minimum and maximum flight levels ( $Z_{\text{min}}$ ,  $Z_{\text{max}}$ ). To produce “column” parameters, we assumed that in situ  $\omega_{\text{LAYER}}$  represents the entire column. To account for this assumption, uncertainty in  $\omega$  of the unsampled column, was adjusted to three times the in situ  $\omega_{\text{LAYER}}$  uncertainty, and combined using a weighted error propagation equation to give an estimate of in situ  $\omega_{\text{COLUMN}}$  uncertainty. Weights were based on the fraction of  $\tau_{\text{COLUMN}}$  sampled, where in situ  $\tau_{\text{COLUMN}}$  is the sum of  $\tau_{\text{BELOW}}$ , in situ  $\tau_{\text{LAYER}}$ , and  $\tau_{\text{ALOFT}}$ .  $\tau_{\text{BELOW}}$  is calculated using the in situ layer mean  $\sigma_e$ , and integrating over the depth of the sub-layer, while  $\tau_{\text{ALOFT}}$  is the AATS-14  $\tau$  measured at  $Z_{\text{max}}$ . The minimum altitude above ground level for all in situ samples ranged from 60–550 m. The majority of these calculated in situ “column” parameters are well characterized by the sampled layer, with, on average, 75% of the aerosol column residing in the sampled layer (range over five sampling events: 58–85%).

### 4. Results of In situ and Remote Sensing $\omega$ Closure Studies

[13] The objective of these comparisons was to empirically establish the uncertainty of in situ  $\omega$  and AERONET  $\omega$ ,

in a robust, independent way, potentially providing two datasets for regional characterization of biomass burning  $\omega$ .

#### 4.1. Closure of $\omega_{\text{LAYER}}$ : In situ Versus Solar Spectral Flux Radiometer (SSFR)

[14] As shown in Table 2, comparisons were made on two days. Good agreement with respect to  $\tau_{\text{LAYER}}$  (in situ versus airborne sun photometry) indicates that the in situ instruments were effectively sampling and measuring the ambient aerosol.

[15] The  $\omega_{\text{LAYER}}$  comparison showed agreement within the estimated uncertainties for 6 September (Table 2), tending to confirm the observational accuracy of both methods. However, the comparison on 24 August indicated a discrepancy beyond the estimated uncertainties. Table 2 shows that  $\tau_{\text{LAYER}}$  was lower by a factor-of-four on 24 August. The SSFR retrieval is governed by the difference between the net fluxes measured at the top and bottom of the layer. When the layer optical depth is small (as on 24 August), the error in this difference is large, resulting in large retrieval error. (Note that estimated retrieval error is 0.09 for this day.) The 24 August comparison may also have been adversely affected by large variability of RH (Table 2) and  $\sigma_s$  (not shown) within the layer.

#### 4.2. Closure of $\omega_{\text{COLUMN}}$ : In Situ Versus AERONET

[16] Comparisons were made at five AERONET sites (Table 3). Horizontal offsets (aircraft profile to AERONET site) ranged from 5–19 km. (Refer to auxiliary material<sup>1</sup> for layer depth and in situ data details). All comparisons show agreement within the estimated uncertainties. The largest discrepancy (0.05 at Sua Pan) may be partially due to a temporal offset − 90 minutes between the AERONET retrieval and the in situ profile. Note that there is a 12% increase in  $\tau_{\text{COLUMN}}$  over this time period (Table 3).

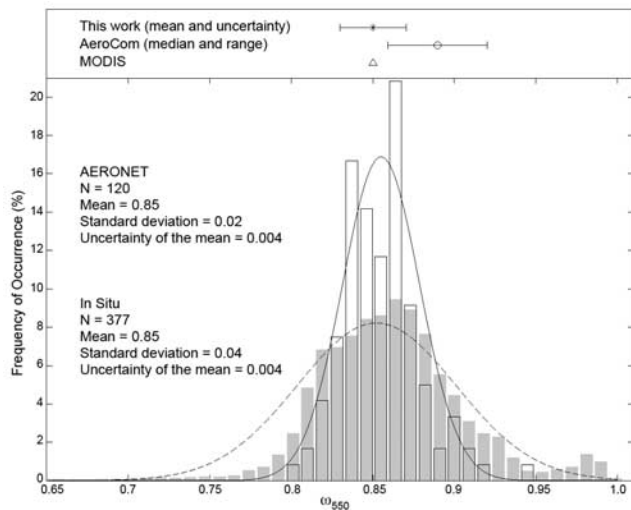
[17] These comparisons provide an independent test of AERONET  $\omega$  retrieval accuracy for biomass burning aerosols. They indicate a root mean square error of 0.03 and a mean systematic discrepancy of −0.01 (Table 3).

### 5. Synthesis

[18] The closure tests indicate that  $\omega_{550}$  measurement uncertainties are well understood. Based on this, we combine AERONET and in situ data from the SAFARI 2000 region and time period (defined here as 14–28°S, and 14–35°E and 10 August to 16 September, 2000, respectively) to

<sup>1</sup>Auxiliary material data sets are available at <ftp://ftp.agu.org/apend/gl/2007gl029697>. Other auxiliary material files are in the HTML.





**Figure 1.** Frequency of occurrence of ambient  $\omega_{550}$  values from AERONET (clear bars) and in situ data (filled bars), with normal probability density functions shown for in situ (dashed line) and AERONET (solid line) distributions. “This work” refers to  $\omega_{550}$  ( $0.85 \pm 0.02$ ), mean  $\pm$  uncertainty, from this synthesis exercise (star); “AeroCom” refers to  $\omega_{550}$  ( $0.89 \pm 0.03$ ), median  $\pm$  range, where range is the mean central diversity for this region, as defined by Kinne *et al.* [2006] (circle); “MODIS” refers to the “highly absorbing smoke model”  $\omega_{550}$  value (0.85) used for aerosol retrievals over land [Remer *et al.*, 2005] (triangle).

estimate a regional-mean value of  $\omega_{550}$  and its uncertainty. We use all data from the AERONET sites listed in Table 3 plus two additional sites, Inhaca Island and Kaoma, in the study region. We use all in situ data except (1) the portions of flights devoted to studying fresh smoke plumes (since these are not regionally representative), (2) samples with  $\sigma_s \leq 15 \text{ Mm}^{-1}$  (because instrumental noise introduces large errors in the calculation of  $\omega$ ), and (3) the rare cases when RH was  $>90\%$  (to prevent cloud contamination).

[19] Figure 1 compares the frequency distributions of  $\omega_{550}$  from the AERONET and in situ datasets. The number of independent data points is estimated based upon a 10 minute time resolution for the in situ data (corresponding to  $\sim 60 \text{ km}$  horizontal and  $\sim 3 \text{ km}$  vertical resolution) and twice daily averages for AERONET, morning and afternoon. Both distributions are roughly Gaussian with a mean of 0.85. The spread of the in situ data is greater, consistent with the fact that it resolves small-scale horizontal and vertical variability. It was noted, that the SAFARI 2000 relative number concentration of soot or black carbon (BC) was twice as large in plumes from flaming combustion compared to smoldering combustion [Pósfai *et al.*, 2003]. This was consistent with an earlier study of African savanna burning, which concluded that savanna fires are efficient emitters of BC, emitting highly absorbing aerosol particles [Andreae *et al.*, 1998]. Therefore, different types of combustion and, distance of samples/AERONET sites from areas of burning will contribute to  $\omega_{550}$  variability.

[20] We suggest that  $0.85 \pm 0.02$  represents the regional mean and uncertainty of  $\omega_{550}$  over Southern Africa during the biomass burning season suitable for use in CTRTMs and

satellite retrieval algorithms. Uncertainty is based upon combining systematic uncertainty (0.01) and in situ and AERONET standard errors (at 95% CI), with a factor of two increase in the latter to account for unknown sampling errors. Figure 1 compares this synthesis value to the range of values used by CTRTMs participating in the AeroCom project [Kinne *et al.*, 2006] for Southern Africa during August and September, 2000. This range is  $0.89 \pm 0.03$ , indicating many of the models overestimate  $\omega_{550}$  for this region. Figure 1 also shows the value of  $\omega_{550}$  used in the MODIS aerosol retrievals over Southern Africa [Remer *et al.*, 2005]. This value is 0.85, consistent with our findings.

[21] The synthesis value of  $\omega$  derived herein ( $0.85 \pm 0.02$ ) strictly applies to the SAFARI 2000 region and time period. It will be important to examine the extent to which this value applies to the entire biomass burning season and to other years. Long term AERONET observations would be appropriate for this purpose.

## 6. Discussion

[22] There are advantages and limitations to both the in situ and AERONET approaches. AERONET data provide excellent temporal coverage but this is limited to specific sites. While the seven AERONET sites used here are broadly distributed, such that regional coverage is good, the aircraft has the advantage of offering access to all locations. Moreover, its ability to sample a wide area in a relatively short space of time provides excellent information on small scale variability. However, the aircraft only samples any particular location for a short time period. The AERONET method directly observes the undisturbed ambient aerosol; however, the retrieval of  $\omega_{550}$  requires a complex inversion with many assumptions and requires high aerosol loading ( $\tau_{440} \geq 0.5$ ). The in situ method is a direct measurement of scattering and absorption that performs well down to modest aerosol concentrations ( $\sigma_s > 15 \text{ Mm}^{-1}$ ); however, it involves removing the aerosol from the ambient environment with potential sampling losses and other artifacts. Clearly, these approaches are complementary. Agreement for collocated comparisons (Section 4) increases confidence in the accuracy of each method. Agreement in the regional means (Section 5) increases confidence that representative sampling was achieved by each method.

[23] As mentioned in Section 1, Version 2 AERONET retrievals of  $\omega$  are lower than those of Version 1 over bright surfaces. The difference can be significant. For example, Haywood *et al.* [2003] reported agreement within 0.01 when comparing in situ derived, spectral  $\omega$  at Etosha Pan to the Version 1 AERONET retrievals. Repeating the comparison using Version 2 data now gives discrepancies  $>0.04$  at each wavelength.

[24] AERONET inversion-based retrievals of  $\omega$  are widely used in climate forcing estimates [Bellouin *et al.*, 2003; Chung *et al.*, 2005; Myhre *et al.*, 2003; Procopio *et al.*, 2004; Sato *et al.*, 2003; Takemura *et al.*, 2002] and in the validation of satellite retrievals [Torres *et al.*, 2005]. The uncertainty of Version 1 AERONET-derived  $\omega$  has been assessed theoretically [Dubovik *et al.*, 2000] but rarely empirically. We are aware of only two prior tests. One, off the U.S. East Coast, indicated a substantial discrepancy

(AERONET lower than in situ by 0.07); however, because of low  $\tau_{550}$  (0.26) and possible sampling errors, the authors could not determine whether this discrepancy was significant [Magi et al., 2005]. Using Version 2 retrieved  $\omega$  data, the discrepancy was reduced to 0.06 (B. Magi, personal communication, 2007). The other is the Haywood et al. [2003] study mentioned above. By providing five direct comparisons and carefully assessing the discrepancies with respect to the estimated uncertainties, the present work adds substantially to current understanding of AERONET retrieval accuracy. However, many more such studies are required before it can be said that AERONET uncertainty and domain of validity for this parameter have been properly assessed.

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