Interactive comment on “Can AERONET data be used to accurately model the monochromatic beam and circumsolar irradiances under cloud-free conditions in desert environment?” by Y. Eissa et al.

Anonymous Referee #1

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SUMMARY AND RECOMMENDATION:

The paper is a detailed and careful analysis of radiative transfer calculations of direct beam and circumsolar irradiances, where aerosol optical properties are characterized by AERONET sunphotometer measurements and inversions. Results show that AERONET characterisation of aerosols allows for an excellent simulation of direct beam irradiances, and for a poorer simulation of circumsolar irradiances, which is still encouraging given the complexity of the measurements in such narrow solid angles.

The paper also presents an interesting comparison of AERONET measurements of aerosol optical depths to similar Sun and Aureole Measurement (SAM) measurements. This suggests that AERONET optical depth may be systematically biased because of its instrument’s relatively wide aperture angle – an important result which deserves more discussion in the paper, as I argue below.

The paper is well-written and should be of interest to Atmos. Meas. Tech. readers. Figures and Tables illustrate the results well. In the discussion, the authors are not able to identify all the causes for biases between radiative transfer calculations and measurements, but they make a good effort considering the many simplifying assumptions that need to be made both on the observational and radiative transfer side. I recommend publication, after minor revisions have been made to address the comments below.

REPLY:

We thank the reviewer for the thorough review of this paper. We address each one of the comments below.

1 Main comments

COMMENT:

• Section 5: When comparing τ_a from SAM and CIMEL, the authors choose to remove measurements where the two instruments disagree by more than ±0.03 (page 7709, line 28), which is the stated accuracy of the SAM. This choice surprises me for two reasons. First, SAM measurements that agree with AERONET could very well be as inaccurate as those that disagree – agreement could very well be coincidental in some cases. Second, the points showing large disagreements are arguably the more interesting to explore. When comparing radiances, the authors justify a similar screening by invoking different cloud shading experienced by the two instruments. Is that also the reason why the two instruments disagree in τ_a 27% of the time? That would seem like a high frequency of occurrence.

It is important to do the comparison in a transparent way, because the result that AERONET AOD may be biased high by 5% is an important one, given that AERONET AOD is taken as ground truth by so many applications, from satellite remote-sensing to global aerosol modelling. This is the first time I hear about such a bias in AERONET, and the authors explanation of the bias being due to the CIMEL instrument’s larger aperture angle makes sense. Is that aperture effect not considered in the AERONET retrieval algorithm at all? Does the authors' result imply that the stated AERONET AOD uncertainty is 0.01 to 0.02 at 0.44 μm should be revised upwards?

REPLY:

We thank you, and the other reviewers, for shedding light on this point. In the revised manuscript we only compare SAM and AERONET AODs, no corrections or filtrations based on the uncertainties applied in the comparison. To remove possibly contaminated measurements, we have filtered out the coinciding samples if their difference is greater than three time the standard deviation of these differences. 150 pairs out of 5024 pairs of samples were excluded. The data sets, figures, text, and tables have been revised in the manuscript accordingly.

Another point brought to our attention by Reviewer #5 is that $\ln(\tau_{a,\lambda})$ versus $\ln(\lambda)$ is not necessarily linear under conditions where the fine mode pollution aerosol prevail. Therefore, in the revised text the following is the method to compute the AERONET reference AOD at 670 nm:

CHANGES IN MANUSCRIPT:

"The AERONET AOD is not provided at the specific wavelength of the SAM instrument of 670 nm. Therefore, the AERONET AOD at this specific wavelength was computed using a second order polynomial fit of AOD versus wavelength using the AERONET measurements of AOD in the interval [440 nm, 675 nm] (Eck et al., 1999) as:

$$\ln(\tau_{a,\lambda}) = a_0 + a_1\ln(\lambda) + a_2\ln(\lambda)^2. \quad (5)$$

This method to compute the reference AOD at 670 nm was selected because the fine mode pollution aerosols, mainly produced by the petroleum industry in the UAE, affect the linear fit of $\ln(\tau_{a,\lambda})$ versus $\ln(\lambda)$ (Eck et al., 2008).

5024 pairs of coincident observations remain, for which the maximum difference in time stamp of both instruments is 1 min. Similar to the cross-comparison of the radiance measurements to remove potentially cloud-contaminated measurements, the standard deviation of the differences between these remaining pairs of observations was computed. All coinciding samples with a difference greater than three times the standard deviation were filtered out. 150 pairs out of 5024 pairs of samples were excluded.

The Fig. 2 exhibits the density scatter plot of the 4874 pairs of SAM versus AERONET AOD at 670 nm. The relative RMSE is 10% and the relative bias is +7% meaning that the SAM $\tau_{a,670\text{ nm}}$ is greater in average than the AERONET $\tau_{a,670\text{ nm}}$. The R^2 value is high at 0.990. Even though AOD values sometimes exceed 0.8, the limits of the axes have been set to have a maximum value of 0.8 in order to better examine the regions with higher sample densities.

There are several interpretations for the discrepancies observed between the SAM and AERONET $\tau_{a,670\text{ nm}}$. The difference in the field of view of both instruments may partially explain such discrepancies, where the AERONET Sun photometer has an aperture half-angle of 0.6°. This implies a portion of the circumsolar radiation is intercepted within the field of view of the instrument, hence a smaller AOD than that observed by SAM. Although in Sinyuk et al. (2012) the error due to the field of view is quantified to be less than the uncertainty in the AERONET AOD retrievals, being 0.01 for $\lambda > 440$ nm.

Another possible cause for such discrepancies is how the Rayleigh scattering and small atmospheric absorption is accounted for at 670 nm in the SAM AOD retrievals. A fixed correction of −0.0556 is used, which was derived empirically by cross calibrations between SAM and AERONET using measurements collected in Oklahoma, USA (Pers. Comm. with J. DeVore and A. LePage, 2015). This fixed correction may induce errors in the SAM AOD retrievals, but it is stated by the team at Visidyne Inc. to be less than the uncertainty of the SAM AOD, being 0.03. Indeed, the bias of 0.02 between AERONET and SAM AOD retrievals is less than the reported uncertainty of the SAM AOD."

COMMENT:

• The authors clearly focus their paper on desert areas, but it would be interesting to discuss in the conclusions whether the method can be reasonably expected to work elsewhere. In many ways, the method does not depend on the origin of the extinction, so it should work for any aerosol type, or even for thin cirrus. As long as the single-scattering albedo and phase function at small scattering angles can be derived, the method would work. Is that correct, or am I overlooking other aspects?

REPLY:

You are correct, given that the optical depth, single scattering albedo and phase function are present the method followed herein should be applicable to other environments. The choice of using a mean value of the single scattering albedo have only been studied using the data set of the desert environment of the UAE, which is why we keep our focus on desert environment.

CHANGES IN MANUSCRIPT:

We add the following text in the conclusion:

"Normally, one should be able to model the monochromatic beam and circumsolar irradiances using the corresponding AERONET data and the presented methodology over any environment. The validations in this study were only performed in a desert environment. The choice of using a mean representative value of the single scattering albedo over other environments is a point which should be addressed first."

2 Other comments

COMMENT:

• Page 7702, line 12: the uncertainty in $E_{0,n,\lambda}$ must also be a large contributor to total uncertainty in computed radiance, doesn't it?

REPLY:

The uncertainty in $E_{0,n,\lambda}$ will contribute to the uncertainty in the diffuse radiance. If we refer to Fig. 1(d) in Harder et al. (2009) it is evident that over a 4 year period the variability of the integrated solar spectral irradiance in the interval [400 nm, 691 nm] is <1%, and more generally ~0%, where the values are relative to a reference value computed from a 10 day window. Therefore, in our application we assume that the uncertainty in the diffuse radiance due to the uncertainty in $E_{0,n,\lambda}$ at the specific wavelength of 670 nm is negligible.

Harder, J. W., Fontenla, J. M., Pilewskie, P., Richard, E. C. and Woods, T. N.: Trends in solar spectral irradiance variability in the visible and infrared, Geophys. Res. Lett., 36(7), 1–5, doi:10.1029/2008GL036797, 2009.

COMMENT:

• Page 7704, line 16: I am not sure I understand the "statistically significant" here. Is that in terms of sampling of the temporal variations in aerosol properties?

REPLY:

We modify the text to read:

"The five remaining months offer larger numbers of samples."

COMMENT:

• Page 7704, line 23: It would be helpful to give basic statistics on the observed τ_a (min, max, standard deviation). I expect that it varies strongly, since there are clear and dusty days in the region.

REPLY:

Good point, we add Table 1 to the manuscript presenting these values for the aerosol optical depth, the single scattering albedo and the phase function for the first three ξ, the values will be presented for the 491 samples where all variables are present and for the 1068 samples do not comprise the single scattering albedo:

Variable	Sample #	Mean	Minimum	Maximum	Standard deviation
$\tau_{a,675\ \mathrm{nm}}$	491	0.500	0.181	1.873	0.209 (42%)
	1068	0.324	0.025	1.873	0.222 (69%)
$P_{a,675\ \mathrm{nm}}(0°)$	491	179.6	73.7	322.6	31.9 (18%)
	1068	173.9	64.7	412.7	41.4 (24%)
$P_{a,675\ \mathrm{nm}}(1.71°)$	491	127.6	48.6	191.3	19.2 (15%)
	1068	120.7	42.3	219.2	23.9 (20%)
$P_{a,675\ \mathrm{nm}}(3.93°)$	491	62.7	21.7	80.4	8.9 (14%)
	1068	58.7	21.4	80.5	10.4 (18%)
$\omega_{a,675\ \mathrm{nm}}$	491	0.954	0.881	0.987	0.019 (2%)
	1068	N/A	N/A	N/A	N/A

CHANGES IN MANUSCRIPT:

In the revised manuscript analyze the statistics of Table 1 as:

"Table 1 presents the mean, minimum, maximum and standard deviation of $\tau_{a,675\ \mathrm{nm}}$, $\omega_{a,675\ \mathrm{nm}}$ and $P_{a,675\ \mathrm{nm}}(\xi)$ for both the 1068 samples (excluding $\omega_{a,675\ \mathrm{nm}}$) and the 491 samples. These statistics are presented for $P_{a,675\ \mathrm{nm}}(\xi)$ for the three ξ smaller than 6° reported in the AERONET Version 2 Inversion product, i.e. 0°, 1.71°, and 3.93°.

The relative standard deviation of $\tau_{a,675\ \mathrm{nm}}$ for the 1068 samples is very large at 69% of the mean value, indicating its great temporal variability and its significance in modelling both the monochromatic $\mathrm{DNI_S}$ and diffuse radiance. The relative standard deviation of $P_{a,675\ \mathrm{nm}}(\xi)$ is also large, ranging between 18% and 24%

for the three smallest ξ for the 1068 samples, again implying its significance in modelling the diffuse radiance.

On the contrary, the relative standard deviation of $\omega_{a,675\text{ nm}}$ is small at 0.019 (2% of the mean value) for the 491 samples. The uncertainty of the AERONET $\omega_{a,675\text{ nm}}$ retrievals is not provided, it is reported at $\omega_{a,440\text{ nm}}$ and is 0.03 (Dubovik et al., 2000). If the multiple scattering effects are ignored, the diffuse radiance is linearly proportional to the single scattering albedo (Dubovik and King, 2000; Liou, 2002; Wilbert et al., 2013). A practical consequence is that a mean value of $\omega_{a,675\text{ nm}}$ can be used with an acceptable loss of accuracy. In addition, using a mean value of $\omega_{a,\lambda}$ is a means to tackle the issue of the missing $\omega_{a,\lambda}$ values at instances when $P_{a,\lambda}(\xi)$ data are available. The AERONET retrievals of $\omega_{a,\lambda}$ are not provided under small aerosol loading situations and this causes the gaps in $\omega_{a,\lambda}$ (Dubovik et al., 2000; Yin et al., 2015).

The mean value of $\omega_{a,675\text{ nm}}$ for the available 491 observations over this study area and for this study period is 0.954, this number is fairly close to the monthly mean values of $\omega_{a,675\text{ nm}}$, which range from a minimum of 0.917 in December 2012 to a maximum of 0.974 reached in March 2013. In the extreme case of the minimum observed value (0.881), an error of 8% will be induced on the diffuse radiance by opting to use a mean value of $\omega_{a,675\text{ nm}}$. However, this is a rare situation. Indeed, 67% of the $\omega_{a,675\text{ nm}}$ samples lie within the mean ± 1 standard deviation and 96% lie within the mean ± 2 standard deviations."

COMMENT:

• Page 7705, lines 8–9: In the context, it should be the other way around: L is proportional to ω_a.

REPLY:

Done. Kindly refer to the revised text from the previous comment.

COMMENT:

• Page 7705, line 14: it is a bit of a nitpick, but "not valid" is slightly inexact. A better word would be "not useable", because the uncertainty in the retrieval of ω_a becomes large at low optical depths, affecting the usefulness of the retrieved value. In fact, it is rather unfortunate that AERONET does not give the uncertainty in ω_a in their products, even in low aerosol optical depth conditions.

REPLY:

The text has been modified as above, we now use "using a mean value of $\omega_{a,\lambda}$ is a means to tackle the issue of the missing $\omega_{a,\lambda}$ values at instances when $P_{a,\lambda}(\xi)$ data are available". The uncertainty of the single scattering albedo is also now reported at 440 nm, see previous text. Unfortunately, we could not find that at 675 nm.

COMMENT:

• Page 7705, line 21: Here again, it would help to give an idea of variability in the phase function by giving basic statistics of the dataset.

REPLY:

Added in Table 1.

COMMENT:

• Page 7706, lines 15–17: Does that mean that CSNI derived from SAM is underestimated? Is it possible to quantify that underestimation?

REPLY:

No, this does not imply the SAM CSNI is underestimated, but there is a gap in the SAM diffuse radiance measurements. In our case when we validate the modelled CSNI with respect to the SAM CSNI we are only validating in the interval [$\delta = 0.52°$, $\alpha = 6°$]. The $\delta = 0.52°$ is selected based on the recommendation of Wilbert (2014).

There is no valid reason to assume the SAM CSNI is underestimated, but if one wants to compute the CSNI from the SAM measurements at $\delta < 0.52°$ then some sort of interpolation need to be applied. In our work we are validating the CSNI in an interval which has no gaps from the SAM measurements.

COMMENT:

• Page 7706, line 26: Does that mean that τ_a is also retrieved from SAM measurements? We would need more details on that procedure, as it would help to better understand point (i) of the quality control described page 7707, line 5.

REPLY:

Yes, the SAM τ_a is retrieved from the SAM measurements (see e.g. LePage et al., 2008; DeVore et al., 2012a). And as you may suspect, why aren't the number of τ_a samples and radiance profiles of SAM equal? Apparently for some reason there are some days where the numbers of samples from the SAM τ_a and SAM profiles do not match. This puzzled us, which is exactly why we added step (i): to eliminate any profiles or τ_a data which do not have a corresponding match.

COMMENT:

• Page 7708, line 23: It would be useful to state here that the actual number of AERONET samples is 10757. That helps the reader determine that the 253 measurements filtered out due to possibly different cloud shading experienced by the two instruments (page 7709, line 1) represent about only 2% of the total, which sounds reasonable if the two instruments are not located too far apart.

REPLY:

In fact there was oversight in this comparison brought to our attention by other reviewers regarding the angles reported with the AERONET almucantar radiance measurements. In the revised text we correct this, explain everything clearly, and add the exact number of samples and distance between the two instruments:

CHANGES IN MANUSCRIPT:

"To compare the AERONET and SAM radiance measurements, the 2241 profiles of AERONET almucantar radiance measurements in the period June 2012 to May 2013 were matched to the SAM horizontal monochromatic radiance measurements which pass the procedures presented in Sect. 4 in terms of time stamp. In the temporal matching process, the measurements between the two different instruments had to be at most 1 min apart and θ_S reported by the two instruments had to match: the bias between the matched θ_S was found to be 0.00° and the maximum absolute error in angle for all observations was 0.22°.

The corresponding ξ of the AERONET almucantar radiance measurements were computed from θ_S and the reported relative azimuth angles. The SAM radiance measurements were then angularly aggregated to match the 0.6° half field of view of the CIMEL 318 Sun photometer using the weighting method described in Wilbert (2014). After matching the measurements, 1067 AERONET and SAM profiles remained. The measurements with the same ξ to the east and west directions of the Sun were averaged to minimize the effects of small pointing errors (Torres et al., 2013). Ideally for these 1067 profiles there should be 5335 measurements of radiance corresponding to the five values from AERONET for $\xi < 6°$, where the maximum ξ from the AERONET measurements was found to be 5.8°. Instead there is a lower number of observations, 5236 to be exact, due to missing data in the almucantar measurements from AERONET which could occur at any ξ. The standard deviation of the differences between these remaining pairs of observations was computed. Then, all samples exhibiting a difference greater than three times this standard deviation were filtered out. This filter is meant to remove extreme cases which could occur if one instrument is shaded by clouds while the other is not. This situation can occur since the two instruments are not exactly at the same place, ~55 m apart, and the time matching is in minutes. 133 pairs out of 5236 were excluded.

The Fig. 1 exhibits the density scatter plot (or 2-D histogram, Eilers and Goeman, 2004) of the SAM and AERONET radiance measurements. Red dots correspond to regions with high densities of samples and the dark blue ones to those with very low densities of samples. The relative RMSE is 14%, the relative bias is 0% and the coefficient of determination R^2 is high at 0.933. The observations are well-scattered around the 1:1 line. The comparison results are good, implying reliable measurements from both instruments. The AERONET measurements were collected at 675 nm while those of SAM were collected at 670 nm. This may induce minor errors in this comparison. Also shown in Fig. 1 are the mean value of the observables on the x-axis, the correlation coefficient (CC), the 1:1 line, the least-squares (LS) affine regression, the robust affine regression, and the first axis of inertia, also known as the first component in principal component analysis (PCA)."

COMMENT:

• Page 7709, lines 13–16: Those details should be given in the Figure caption instead.

REPLY:

We prefer to keep these details in the text, because the same applies to Figs. 1-2 and 4-6 in the manuscript.

COMMENT:

• Page 7709, line 26: Another nitpick, but surely AERONET's accuracy is the one that is greater than SAM, not the other way around.

REPLY:

You are right. In any case this text has been removed, we are not removing any samples based on the stated uncertainties of SAM or AERONET.

COMMENT:

• Page 7710, line 6: “exceed” -> “sometimes exceed”

REPLY:

Done.

COMMENT:

• Page 7711, lines 16 and 21: “abbreviated in” -> “abbreviated as”

REPLY:

Done.

COMMENT:

• Page 7713, lines 14–16: Supplying hundreds of Legendre moments does not sound so terrible with current computers. Is the reader supposed to understand that it is in fact impractical?

REPLY:

Yes, it is not so terrible. In fact even with the three parameter TTHG phase function one would still need to compute the hundreds of Legendre moments from those three parameters before passing on the inputs to libRadtran. The main advantage of using the three parameter TTHG phase function is stated in the text:

“This opens up the path for a model to be developed to estimate the three parameters of the phase function, rather than estimating the hundreds of Legendre moments required to accurately represent the phase function.”

COMMENT:

• Page 7714, lines 3–4: A more common method to deal with phase functions with sharp forward scattering peaks is the delta-Eddington approximation, where the peak is truncated and SSA and g scaled accordingly (Joseph, Wiscombe, and Weinman, J. Atmos. Sci., 33, 2452–2459, 1976). The truncated phase function is easily represented with a few 10s of Legendre coefficients. Did the authors consider that method, but found it unsatisfactory?

REPLY:

No, we did not consider that for this study. Back to the previous point, the TTHG phase function very well captures the sharp peaks of the phase function with only three parameters.

COMMENT:

• Page 7715, line 5 and page 7716, line 6: How is the vertical profile of aerosols specified?

REPLY:

It is not. The atmospheric profile is defined as mid-latitude summer and the aerosol optical depth at ground level is provided in the inputs.

COMMENT:

• Page 7715, line 20 and page 7716, line 12: What are the characteristics of the OPAC desert type and DESERTMAXaerosolmodels?

REPLY:

Good point.

CHANGES IN MANUSCRIPT:

We add the following text in the results and discussion:

"The underestimation of the circumsolar effect by SMARTS may partly be explained by an incorrect phase function that was hard-coded for all desert aerosol types in v2.9.5 of the code (Pers. Comm. with C.A. Gueymard, 2015). The large underestimation of the DESERT_MAX single scattering albedo, being 0.7 as opposed to the mean value from AERONET of 0.954, also contributes to the observed bias.

The aerosol optical properties extracted from the OPAC library are in fact not too far off from the AERONET means: $g_{675\ \mathrm{nm}} \approx 0.71$ and $\omega_{a,675\ \mathrm{nm}} \approx 0.91$ as opposed to the mean values from AERONET of 0.699 and 0.954 respectively. The OPAC properties are not provided at the exact wavelength of interest, but were determined by observing the values provided at 650 nm and 700 nm at a relative humidity of 70% and 80% (http://andromeda.caf.dlr.de/data-products/spectroscopy-data/optical-properties-aerosols-and-clouds-opac, last accessed: 16/09/2015). These values of relative humidity were selected based on the relative humidity at the surface for the mid-latitude summer profile, which is 75.7% (cf. Table 3.1 in Gueymard, 1995). This implies that the aerosol phase function computed by libRadtran using the OPAC desert model is not able to depict the sharp peaks at the smallest ξ."

COMMENT:

• Page 7716: It is unnecessary to give the variable names and state which output option was selected. Scientific details are important for reproducibility but at the same time the paper is not supposed to be a user manual for SMARTS.

REPLY:

OK, the variable names have been removed from the list of inputs.

COMMENT:

• Page 7718, lines 1–3: How would that kind of errors affect the comparison of SMARTS to SAM?

REPLY:

It was meant that these kinds of errors may affect both SMARTS and libRadtran modelled values, not only SMARTS, i.e. if there is a misalignment or miscalibration error in the AERONET data those would pronounce some errors in the modelled values and hence on the comparison with the SAM reference values.

CHANGES IN MANUSCRIPT:

To avoid any confusion, the text is revised:

"Other sources of errors in both the SMARTS and libRadtran estimates may be due to a miscalibration of the AERONET Sun photometer, or misalignments in its tracking mechanism (Dubovik et al., 2000)."

COMMENT:

• Page 7719, lines 3–11: It would be informative to identify which of the characteristics of the aerosol models is responsible for the poor fit. For example, the OPAC desert aerosol model has a single-scattering albedo of 0.89, which is outside the range observed by AERONET in this study. That could account for some of the errors in radiative transfer calculations of the CSNI.

REPLY:

Done, see three points above.

COMMENT:

• Figure 7: Circles are not a very accurate way to represent data on a graph. Could we have crosses instead?

REPLY:

The figure has been split in to two separate figures, one showing Oct to Dec 2012, and another for the rest of the months. Crosses are now used in both figures.