Manuscript title: “Can AERONET data be used to accurately model the monochromatic beam and circumsolar irradiances under cloud-free conditions in desert environment?”

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OVERALL COMMENTS

This manuscript presents a detailed analysis comparing simulated direct beam irradiances and circumsolar irradiances with corresponding measurements using the SAM instrument. AERONET data are also used, both for comparing with SAM and as a source of radiative properties of aerosols used as input to radiative transfer models. This is an interesting topic and the manuscript is mostly clearly written. However, it seems to me that the authors do not discuss in proper detail the various sources of uncertainties that influence their analysis. In particular, the conclusion that AERONET underestimates the AOD because of its field-of-view is too strong, in my opinion. Thus, I find that the manuscript could be suitable for publication in AMT after important improvements.

REPLY:

Thank you for your review. We provide a response to each one of the points you bring up.

Areas that need to be improved

1. The manuscript would need to consider and discuss all sources of uncertainty in SAM, AERONET, and radiative transfer model results. This is an overarching item that connects to many parts of the manuscript. I try to give some examples below.

a. Eq. 1 is true from a radiative transfer theory point of view, but does not agree with the definitions of DNI and DNI_S given in the Introduction. In RT theory, the direct radiation is usually defined as radiation originating from the Sun that has neither been scattered nor absorbed. In DNI measurements (as defined in the Introduction), the DNI will always contain a component of forward scattered radiation even for an instrument with sufficiently narrow field-of-view.

REPLY:

This is true, although not possible to quantify from the point of view of the ground measurements in the extent of the solar disc.

CHANGES IN MANUSCRIPT:

We modify the text to read:

"In radiative transfer modelling, the monochromatic DNI_S only comprises photons that were not scattered and is represented by the Beer-Bouguer-Lambert law (Liou, 2002) as:

$$B_{n,\lambda}^{strict} = E_{0,n,\lambda} \exp(-\tau_\lambda m), \quad (1)$$

where $B_{n,\lambda}^{strict}$ is the monochromatic DNI_S from radiative transfer modelling point of view, $E_{0,n,\lambda}$ is the monochromatic extraterrestrial irradiance received on a plane normal to the Sun rays, τ_λ is the monochromatic optical depth of all attenuating factors present in the atmosphere and m is the pressure-corrected relative optical air mass (Kasten and Young, 1989). Therefore, accurate modelling of $B_{n,\lambda}^{strict}$ requests an accurate retrieval of τ_λ within the extent of the solar disc only.

For ground measurements of the monochromatic DNI_S it is not possible to distinguish whether a photon was scattered or not before reaching the measuring instrument (Blanc et al., 2014). Therefore, in this work it is assumed that the effects of scattered photons within the extent of the solar disc are negligible, and $B_{n,\lambda}^{strict}$ is validated against the ground reference monochromatic DNI_S, noted $B_{n,\lambda}^{Sun}$. To this end, the monochromatic DNI_S modelled by the radiative transfer codes is also noted $B_{n,\lambda}^{Sun}$."

b. The effect of forward scattered radiation on AERONET AOD has been discussed in a paper by Sinyuk et al. (GRL, L23806, 2012; perhaps also elsewhere).

REPLY:

Thank you for this reference. We add it to the analysis. In fact we change the whole analysis of the comparison between the SAM and AERONET AOD. No more correction of AERONET AOD, and no more filtering of samples based on the uncertainty of either of the instruments.

CHANGES IN MANUSCRIPT:

The modified analysis reads:

"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 $\tau_{a,670\ \mathrm{nm}}$. 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."

c. From eq. 1, it is clear that even a small systematic difference (error) in E_0 will have an effect on the analysis presented. This is not discussed in the manuscript. How well is E_0 known? Is the same E_0 used in radiative transfer models and in AERONET and SAM aerosol retrievals?

REPLY:

To some extent, but if we observe the nine extraterrestrial solar spectra available with the SMARTS code we find that at 670 nm the minimum value is 1509 $Wm^{-2}\mu^{-1}$ and the maximum is 1539 $Wm^{-2}\mu^{-1}$, i.e. the difference will be around only ~2% in the modelled diffuse radiance between such spectra.

In the revised manuscript we have selected the same spectrum in both libRadtran and SMARTS to avoid any spectral mismatch when different spectra are used. We now use that of Gueymard (2004). All text, figure and results have been updated accordingly.

Regarding the second, I have contacted the team at Visidyne Inc., and their response was that they do not use the same spectrum as AERONET, but then they do calibrate their AOD values against those of AERONET. Which then makes the AERONET AOD correction redundant, and hence no longer proposed.

d. P7706, L10-12: SAM circumsolar radiances are accurate to ~5 to 15%. This uncertainty is mentioned here, but thereafter it is given little emphasis. What exactly does it mean that the relative error is, e.g., 15%? If SAM circumsolar radiances have a systematic bias of 15%, then that would more or less explain the difference seen in Fig. 6. This brings to my mind a major challenge of this manuscript: when comparing data from various sources, which all have their uncertainty, how can one know what the truth is? For example, why do the authors choose to correct AERONET data using SAM as a reference, what are the scientific evidence saying that SAM is truly better?

REPLY:

Firstly, in the revised manuscript there is not more AERONET AOD correction. Secondly, we shed some light on errors in the SAM reference data in the results and discussion section.

CHANGES IN MANUSCRIPT:

"Other errors may in fact be due to the reference SAM measurements. For example, the monthly relative bias for November 2012 from the radiance measurements comparison (cf. Fig. 1) is +23%, where the SAM radiance measurements are overestimated in average with respect to the AERONET radiance measurements. This comparison for November agrees with the similar comparison performed by Wilbert (2014), and is partly explained by the broken entrance window of the SAM instrument. This would in turn induce a larger underestimation in the CSNI in this month.

Indeed, it is observed that the CSNI is underestimated in November 2012 by −39%."

And:

"Nevertheless, given the uncertainty of the SAM instrument in the aureole region to be ~ 15%, it is concluded that defining the moments of the TTHG PFCN in libRadtran provides an overall remarkably accurate and interesting estimates of the monochromatic CSNI under cloud-free conditions over the study area."

And in the conclusion:

"The underestimation of the modelled CSNI is mainly attributed to errors in the SAM reference measurements and the AERONET aerosol phase function. It is believed that a better representation of the aerosol phase function $P_{a,675\text{ nm}}(\xi)$ for the smallest ξ than the one provided by AERONET would further improve the modelling results of the CSNI. Given the uncertainty of the SAM radiance measurements in the aureole region to be ~15%, it is safe to say that the methodology presented herein provides a very accurate estimate of the CSNI."

e. Modeling circumsolar irradiances using libradtran may require extra efforts. The paper by Reinhardt et al. (AMT, doi:10.5194/amt-7-823-2014), including authors from the libradtran team, chooses to use Monte Carlo simulations for simulating the circumsolar radiances. This could be a better approach than the one chosen in the present manuscript. The reason for this is: If I understand correctly, it becomes difficult to realistically calculate the circumsolar irradiance (i.e., integrate over the chosen solid angle) when choosing the disort solver with 16 streams. With 16 streams, there are 8 discrete streams (directions) in the downwelling hemisphere. How can one get a realistic value for the integrated circumsolar irradiance (narrow solid angle) from only 8 streams? (note that the same problem exists still for 32 streams)

REPLY:

This is a very good point. In fact, in we have corresponded with B. Reinhardt via email in October 2013 regarding the libRadtran version he is using. The response was it is in-house version, and it was not yet decided whether or not to include it in the future releases of libRadtran, at least at that time.

Also, in Reinhardt (2013) he shows that using the OPAC desert aerosol model the differences in modelling the radiance are negligible when comparing MYSTIC, and DISORT using 16, 32 and 64 streams.

CHANGES IN MANUSCRIPT:

In any case we add the following text in Sect. 6 to shed light on this:

"It is worth noting that Monte Carlo radiative transfer solver MYSTIC is also available in libRadtran, and was used by Reinhardt (2013) and Reinhardt et al. (2014). It has several advantages over the DISORT solver: it assumes 3-D geometry, it assumes the Sun is an extended source with a finite diameter, and it more accurately handles the phase functions with extremely sharp peaks. However, in the public version of libRadtran the MYSTIC solver assumes 1-D geometry, and assumes the Sun as a Dirac function. Moreover, it can only compute the radiance at one viewing direction at a time, whereas DISORT can model the radiance at multiple directions using one input file. Besides, the DISORT solver is significantly faster than the MYSTIC solver. Finally, the modelling of the radiance when using a desert aerosol model is practically the same from the MYSTIC and DISORT solvers, the same is not true though under cirrus cloud conditions (Reinhardt, 2013). Therefore, in this work DISORT was the selected solver when using libRadtran."

f. Modeling circumsolar irradiances: the actual surface pressure is not taken into account. How big influence could that have on your calculations?

REPLY:

In our study it is provided from the atmospheric profile, mid-latitude summer of Anderson et al. (1986) in this case. However, we have not studied the effects of varying the surface pressure only on our calculations.

g. P7719, L19-23: The fact that AERONET measurements are only made for angles larger than 3 degrees, although the phase function is reported also for the very forward directions is interesting. It means, in practice, that AERONET somehow (how?) determines the phase function also for the angles that are not measured. Considering how closely this manuscript is looking into the small differences between SAM and RTM/AERONET, I think this fact could be given some more emphasis (or be said more clearly) in the manuscript.

REPLY:

In the manuscript we emphasize this point through Figs. 7 and 8 and the results and discussion section.

CHANGES IN MANUSCRIPT:

The following text appears in the results and discussion:

"The residuals of the libRadtran and SAM monochromatic CSNI versus the AERONET $P_{a,675\ \mathrm{nm}}(\xi = 0°)$ are exhibited in Fig. 7 for the months of June, July, September 2012, and January, February, March, April, 2013, and Fig. 8 for the months of October, November, December 2012. Although the number of samples is relatively low for the AERONET $P_{a,675\ \mathrm{nm}}(\xi = 0°)$ with the sharpest peaks, it is evident that the underestimation is greater in the negative direction for the AERONET $P_{a,675\ \mathrm{nm}}(\xi = 0°)$ with the sharpest peaks. This observation supports the hypothesis that the AERONET $P_{a,675\ \mathrm{nm}}(\xi)$ might not be very accurate for the smallest ξ, especially for those with the sharpest peaks. It is also evident in Fig. 8 that the larger underestimation of October and December 2012 is due to the underestimation in the libRadtran monochromatic CSNI for the $P_{a,675\ \mathrm{nm}}$ with the sharper peaks. However, the same cannot be said for November 2012, because $P_{a,675\ \mathrm{nm}}(\xi = 0°)$ have relatively moderate values but the modelled libRadtran monochromatic CSNI generally exhibit a larger underestimation than other samples with similar values of $P_{a,675\ \mathrm{nm}}(\xi = 0°)$. Again this is due to an overestimation in the SAM radiance measurements for this month."

2. Minor comments/suggestions

a. P7700, L22-25: Would be interesting to have a number (order of magnitude) on how significant/important it is to have both CSNI and DNI_S

CHANGES IN MANUSCRIPT:

We modify the text as:

"In desert environments the circumsolar radiation may be significant under turbid cloud-free skies, implying that information of the CSNI and DNI_S is essential for an improved assessment of the DNI (Blanc et al., 2014). For example, Thomalla et al. (1983) report a CSR of 0.06 for an aperture half-angle of 5° when using a desert aerosol model for a solar zenith angle of 70° and an aerosol optical depth (AOD) at 550 nm of 0.4."

b. P7703, L6: How close by are the two instruments?

CHANGES IN MANUSCRIPT:

We revise the text as:

"It has an altitude above mean sea level of 2 m, and is located at 24° 26' 30.58'' N,54° 36' 59.75'' E. Coinciding AERONET and SAM measurements were performed from June 2012 to May 2013, the instruments are ~55 m apart and measurements are still ongoing."

c. P7704, L17-18: aerosols contribute most when no clouds are present

REPLY:

Actually we removed this section from the text.

CHANGES IN MANUSCRIPT:

And added the following:

"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 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 $\omega_{a,675\ \mathrm{nm}}$ is small at 0.019 (2% of the mean value) for the 491 samples. The uncertainty of the AERONET $\omega_{a,675\ \mathrm{nm}}$ retrievals is not provided, it is reported at $\omega_{a,440\ \mathrm{nm}}$ 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 $\omega_{a,675\ \mathrm{nm}}$ 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 $\omega_{a,675\ \mathrm{nm}}$ 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 $\omega_{a,675\ \mathrm{nm}}$, 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. ”

d. P7709, L24-: I agree with the other reviewer. It seems unclear why data pairs having a difference larger than 0.03 should be removed.

REPLY:

No more filtrations based on uncertainties (cf. point 1-b above).