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Aerosols Attenuating the Solar Radiation Collected by Solar Tower Plants: the Horizontal Pathway at Surface Level

Thierry Elias[1, a)], Didier Ramon[1], Laurent Dubus[2], Charles Bourdil[2], Emilio Cuevas-Agulló[3], Taoufik Zaidouni[4], Paola Formenti[5]

[1] HYGEOS, Euratechnologies, 165 avenue de Bretagne, 59000 Lille, France
[2] EDF R&D, 6 Quai Watier, 78400 Chatou, France
[3] AEMET, C/ La Marina, 20, Planta 6, 38001 Santa Cruz de Tenerife, Spain
[4] DMN/DTE, Casablanca, Morocco
[5] LISA, UMR CNRS 7583, Université Paris Est Créteil et Université Paris Diderot, IPSL, France

a) corresponding author: te@hygeos.com

Abstract. Aerosols attenuate the solar radiation collected by solar tower plants (STP), along two pathways: 1) the atmospheric column pathway, between the top of the atmosphere and the heliostats, resulting in Direct Normal Irradiance (DNI) changes; 2) the grazing pathway close to surface level, between the heliostats and the optical receiver. The attenuation along the surface-level grazing pathway has been less studied than the aerosol impact on changes of DNI, while it becomes significant in STP of 100 MW or more. Indeed aerosols mostly lay within the surface atmospheric layer, called the boundary layer, and the attenuation increases with the distance covered by the solar radiation in the boundary layer. In STP of 100 MW or more, the distance between the heliostats and the optical receiver becomes large enough to produce a significant attenuation by aerosols. We used measured aerosol optical thickness and computed boundary layer height to estimate the attenuation of the solar radiation at surface level at Ouarzazate (Morocco). High variabilities in aerosol amount and in vertical layering generated a significant magnitude in the annual cycle and significant inter-annual changes. Indeed the annual mean of the attenuation caused by aerosols over a 1-km heliostat-receiver distance was 3.7% in 2013, and 5.4% in 2014 because of a longest desert dust season. The monthly minimum attenuation of less than 3% was observed in winter and the maximum of more than 7% was observed in summer.

INTRODUCTION

Attenuation of the solar radiation by aerosols is recognised as a determinative factor in assessing the productivity of a solar tower plant (STP). The impact of aerosols on the solar irradiance, incident at surface level, has indeed been studied by several authors [e.g. 1]. With increasing STP productive potential and subsequent increasing heliostat field area, a further component of the attenuation by aerosols needs to be evaluated. Aerosols attenuate the solar radiation not only in the downwelling trajectory to the heliostat, but also in the pathway between the heliostat and the optical receiver, close to the surface level. The surface level attenuation is significant, as aerosols mostly lay within the surface atmospheric layer, called the boundary layer, and the attenuation increases with the distance between the heliostat and the optical receiver. Measurements are necessary to resolve the large variability of the aerosol properties, in time and in space.

Pyrheliometers were proposed by other authors to estimate the surface level attenuation [2], while we propose to exploit sunphotometer measurements which are dedicated to aerosols. In situ measurements of the atmospheric scattering/extinction can also be used [3], but we preferred in this work to exploit the data taken by the AErosol RObotic NETwork (AERONET [4]), which are the most precise on aerosol extinction, and furthermore worldwide available. However AERONET delivers column-integrated aerosol parameters while we need parameters resolved at surface level. Tahboub et al. [2] proposed a constant relation between surface level and column parameters. Here we consider the seasonal change of the atmospheric layering by using the boundary layer height estimated by the European Centre for Medium-range Weather Forecast (ECMWF) operational analysis. Our method provides the inter-annual and seasonal variabilities of the attenuation by aerosols at surface level, at remote sites. The method is applied on data collected at Ouarzazate in Morocco.

Data and method are presented and the method is validated for Ouarzazate, using figures presented in the literature. The limitation of the method is also shown, using data acquired at Banizoumbou (Niger). The annual cycle and the inter-annual variabilities of the attenuation at Ouarzazate are eventually commented.

DATA AND METHOD

The method proposes to exploit observation data to estimate the attenuation of the solar radiation by aerosols, in the pathway between the heliostat and the optical receiver, at local scale, at remote sites, and with a high temporal resolution. Ground-based aerosol data are used here with the perspective to apply such a method on satellite data. We consider two sites to show the applicability of the method in function of the specific aerosol vertical layering, and several years of data are used to show the inter-annual and seasonal variabilities of the attenuation. Computations are made at wavelengths representative of the solar radiation, at 440 and 500 nm.

Definitions of Relevant Aerosol Optical Properties

The impact of aerosols on the incident energy is expressed by the transmittance, which concerns both the column and surface-level optical pathways (Fig. 1). The transmittance is expressed in function of the aerosol optical thickness which is measured.

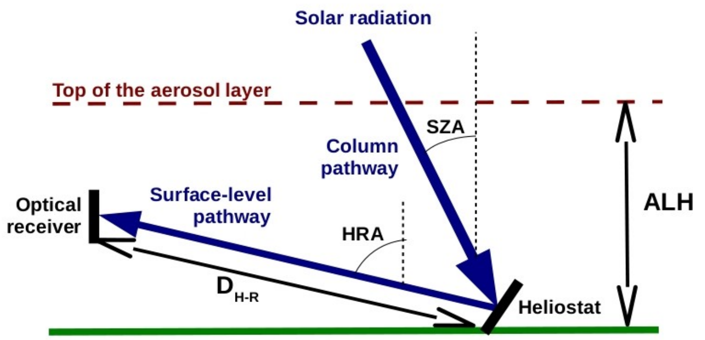

FIGURE 1. The two pathways of the collected solar radiation in a STP, the corresponding *ALH* and $D_{H\text{-}R}$ distances and the SZA and HRA angles.

Transmittance and attenuation

The transmittance *T* describes the proportion of electromagnetic radiation which is transmitted through a scattering and absorbing medium [e.g. 3]. With incident radiative flux I_0, the transmitted radiative flux I_t is:

$$I_t = I_0 \, T, \quad (1)$$

In the atmosphere, the transmittance is reduced because of particles and gases [e.g. 5]. Particles in suspension in the atmosphere are fog and cloud droplets, and aerosols. In agreement with the STP running conditions, we deal here with 1) clear-sky conditions, i.e. without clouds between the sun and the heliostats, and 2) relatively dry conditions, i.e. without fog between heliostats and the optical receiver. Cloud and fog droplet particles are consequently disregarded. Both molecules and aerosols affect the transmittance in clear-sky conditions, as:

$$T = T_{Ray} \, T_{gas} \, T_{aer} \quad (2)$$

The aerosols are main atmospheric components responsible for the transmittance variability, as the transmittance due to molecular scattering T_{Ray} can be precisely computed by the Rayleigh theory in function of the atmospheric pressure and wavelength, and is fairly constant at a defined site, and the transmittance due to gas absorption T_{gas} is negligible at considered wavelengths (T_{gas}=1.0). The attenuation *A* is derived from the transmittance as:

$$A = 1 - T \quad (3)$$

The aerosol component

According to the Beer-Lambert law, the transmittance is:

$$T = \exp\left(-\int_0^L EC(l)\,dl\right) \tag{4}$$

L is the length of the scattering and absorbing medium crossed by the radiation, and the extinction coefficient EC may be heterogeneous in the crossed medium. For the STP, it is necessary to know the transmittance along two pathways: column and surface-level (Fig. 1). The transmittance caused by aerosols along the atmospheric column $T_{aer,col}$ is expressed as:

$$T_{aer,col} = \exp\left(-\frac{AOT}{\cos(SZA)}\right) \tag{5}$$

The aerosol optical thickness A*OT* being defined along the vertical:

$$AOT = \int_0^{ALH} AEC(z)\,dz \tag{6}$$

ALH is the aerosol layer height and the aerosol extinction coefficient *AEC* may dependent on the altitude *z*. From Eq. 4, the transmittance at surface level $T_{aer,surf}$ along the pathway from the heliostat to the receiver [e.g. 3] is expressed as:

$$T_{aer,surf} = \exp\left(-\int_0^{D_{H-R}} AEC(l)\,dl\right) \tag{7a}$$

D_{H-R} is the distance between the heliostat and the optical receiver (Fig. 1).

Methodology

Thereafter, $T_{aer,surf}$ is written T_{aer} for simplification. In the hypothesis of constant aerosol extinction coefficient from surface level up to *ALH*, Eq. 7a is simplified as:

$$T_{aer} = \exp\left(-AEC\ D_{H-R}\right) \tag{7b}$$

In the hypothesis of a unique and uniform aerosol layer (UUAL hypothesis) of height *ALH*, the transmittance is expressed as:

$$T_{aer} = \exp\left(-\frac{AOT}{ALH} D_{H-R}\right) \tag{7c}$$

where Eq. 6 is simplified such as:

$$ALH = \frac{AOT}{AEC} \tag{8}$$

Eq. 7c is equivalent to the Eq. 7 of Sengupta and Wagner [6] with AOT/ALH = Y/250, Y being the aerosol optical thickness in the layer of 250 m height [6]. Similarly to Eq. 5 for the whole atmosphere, T_{aer} can also be written as:

$$T_{aer} = \exp\left(-\frac{AOT(\text{height of the tower})}{\cos(HRA)}\right) \quad (9)$$

where *HRA* is the heliostat-optical reciever angle (Fig. 1). We propose a method to estimate T_{aer} from observations and in the UUAL hypothesis, replacing *ALH* by the boundary layer height (BLH) computed in the operational analysis by ECMWF, and $D_{H\text{-}R}$ is assumed to be 1 km:

$$T_{aer} = \exp\left(-1000 \times \frac{AOT}{BLH}\right) \quad (10)$$

Eq. 6 of Tahboub et al. [2] gives a constant height of around 4 km for a whole year while here *BLH* varies with the season. Computations are made with monthly averages. For the validation, the question we want to check is “Can we use the boundary layer height of the ECMWF operational analysis as a proxy to convert *AOT* in aerosol extinction coefficient at surface level, and to compute the transmittance along the surface-level grazing pathway ?”. *BLH* is consequently compared to *ALH* (Eq. 8) in the Validation Section. Next section describes the site characteristics, by commenting both *AOT* and the *AOT* spectral dependence expressed by the Ångström exponent (AE) as:

$$AE = -\frac{\ln\left(\frac{AOT(\lambda_1)}{AOT(\lambda_2)}\right)}{\ln\left(\frac{\lambda_1}{\lambda_2}\right)} \quad (11)$$

where λ is the wavelength.

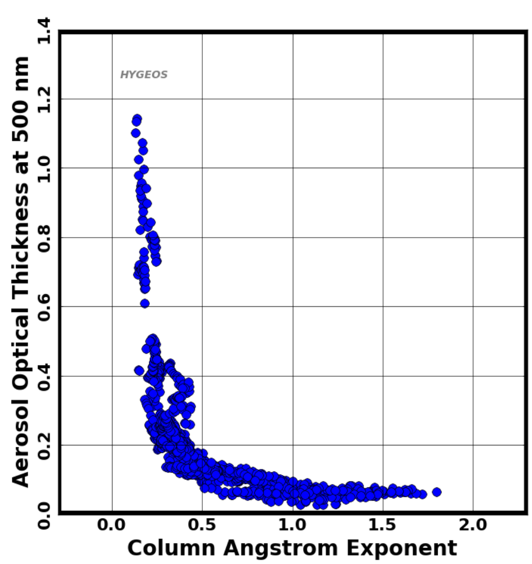

FIGURE 2. Correlation between Aerosol optical thickness at 500 nm and the Ansgtrom exponent at Ouarzazate in June 2013 (level 1.5 AERONET data), averaged at 15-min resolution.

Data

AOT was measured at two stations of AERONET: Ouarzazate in Morocco (30.92°N, 6.91°W, 1136 m above sea level (a.s.l.)) and Banizoumbou in Niger (13.54°N, 2.66°E, 250 m a.s.l.). *AOT* was measured at 440, 675, 870, and 1020 nm at Banizoumbou and at Ouarzazate. The data quality level available by internet is 2.0 at Banizoumbou in 2006, 2.0 at Ouarzazate in 2012 and 1.5 at Ouarzazate in 2013 and 2014.

BLH was extracted from the operational analysis by ECMWF. The spatial resolution is 0.125°x0.125° and the temporal resolution is 3 hours. *AEC* measured by a TSI nephelometer at Banizoumbou [7] during the AMMA field experiment campaign is used to show the limits of the UUAL hypothesis. The air sample was dried, and measurements were made at three wavelengths: 450, 550, and 700 nm.

Site Description

Three sites of North West Africa are referred to, which are representative of North-Western Maghreb (Ouarzazate), Sahara (Tamanrasset), and Sahel (Banizoumbou) [8].

The annual cycle of AOT at Ouarzazate and Tamanrasset

Figure 2 shows that Ouarzazate was affected by desert dust: the Ångström exponent (Eq. 11) decreased for increasing *AOT*. Monthly averages of *AOT* during three years are shown in Fig. 3. The desert dust events repeatedly affected *AOT* values at Ouarzazate in June-August: *AOT* at 500 nm reached the annual maximum of around 0.40 in August 2012 and 2014 and of around 0.21 in July 2013. At a 15-min resolution, *AOT* was observed larger than 0.60 during these months and could even reach 1.00 (Fig. 2). Similarly, the maximal value observed in May-June 2006 during the SAMUM campaign was 0.80 [9]. The minima, smaller than 0.05, were generally observed in November-January (Fig. 3).

Similarities were observed with the AERONET site of Tamanrasset: values of *AOT* were smaller than 0.10 in November-January 2006-2009, and values of *AOT* were around 0.40 in July-August [10, 11]. However, the desert dust season started earlier in Tamanrasset in 2006-2009 where *AOT* was 0.40 in April while it was smaller than 0.15 in Ouarzazate in 2012-2014.

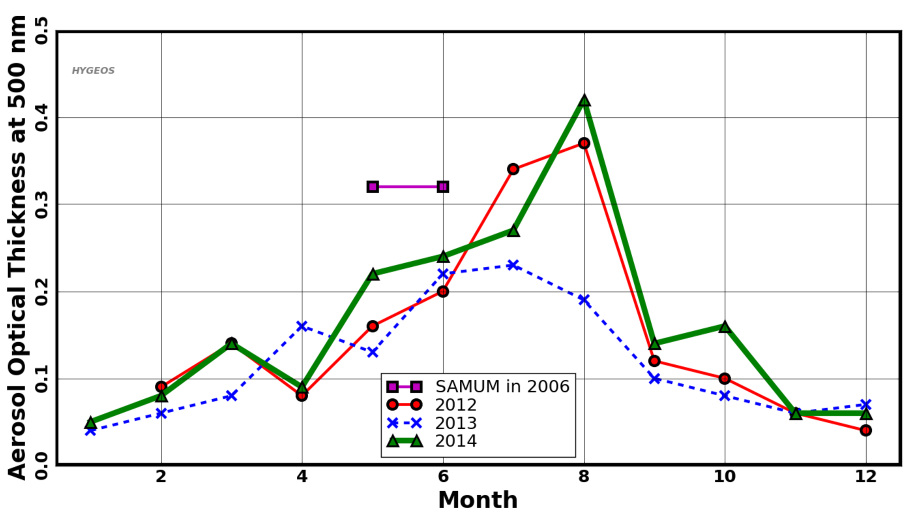

FIGURE 3. Annual cycle of *AOT* measured at 500 nm at the AERONET station of Ouarzazate during three years. Month averages are given. The SAMUM value is also shown.

The inter-annual variability of AOT at Ouarzazate

The desert dust season was longer in 2014 than in 2012 and 2013, starting earlier and ending later, with a noticeable impact on the annual average of *AOT*. *AOT* was larger in September and October 2014 than in 2012 and 2013 (Fig. 3), and the increase of *AOT* started in May in 2014 while it started in June in 2012 and 2013. The annual mean of *AOT* at Ouarzazate was 0.11 in 2013 and 0.15 in 2014, smaller than the global average over land of around 0.19 [12]. The desert dust season may have been longer in 2006 than in 2012-2014, as the mean value of *AOT* during one month in May-June was 0.32 [9], larger than in 2012-2014.

Different annual cycle at Banizoumbou

In winter, strong Harmattan winds transport desert dust from Sahara [11]. Banizoumbou shows a different annual cycle [11] with a monthly maximum in *AOT* in April and not in August, and of a value twice larger.

VALIDATION

We make comparisons between *ALH* (Eq. 8) and *BLH* for two sites. We show that at Ouarzazate the UUAL hypothesis was validated, *ALH* and *BLH* agreeing. However at Banizoumbou the aerosol layer was not homogeneous and the transmittance would be significantly under-estimated using Eq. 10.

Unique and Uniform Aerosol Layer At Ouarzazate During the SAMUM Campaign

AOT was 0.32 at Ouarzazate in May-June 2006 during the SAMUM campaign, and *AEC* was 100±50 Mm^{-1} [9]. Consequently *ALH* was around 3.2 km (Eq. 8). *BLH* was similar with values varying between 2.9±0.7 and 3.6±0.7 km at 12-15:00 in May-June 2011-2014. *BLH* could therefore be used to convert *AOT* in *AEC* in May-June 2006 in Ouarzazate. This is consistent with lidar measurements made at Ouarzazate during the SAMUM campaign, which show a homogeneous aerosol layer from surface to top (Fig. 4).. Applying the UUAL hypothesis for all months at Ouarzazate, the transmittance can be computed for the three years of *AOT* data (***Section 4***).

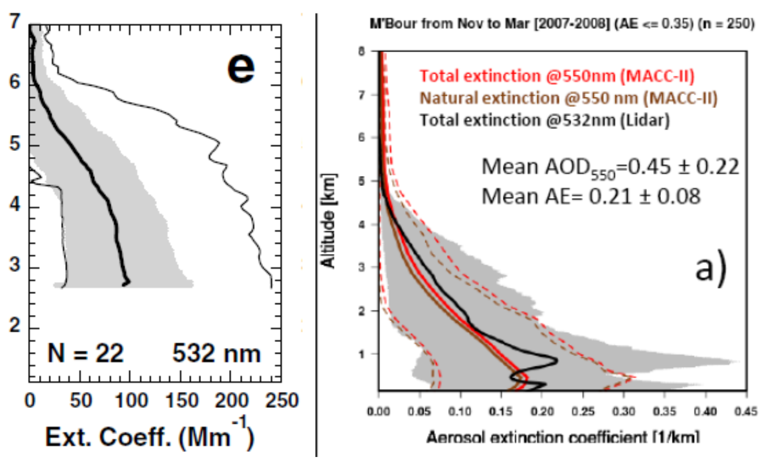

FIGURE 4. Vertical profiles of *AEC* measured at Ouarzazate [9] (left) and at M'Bour [8] (right) by ground-based lidars.

Two layers At Banizoumbou in winter during the AMMA campaign

ALH at Banizoumbou is computed using *AEC* measured at 450 nm by the nephelometer and *AOT* measured at 440 nm by AERONET (Eq. 8). The monthly average of *ALH* was 3.7±1.9 km in January 2006 and 2.6±1.4 km in February 2006. In February *ALH* was mostly around 2.0 km, while in January, it frequently ranged from 2.0 to 3.6 km. According to the lidar measurements at M'Bour (Fig. 4), *ALH* would be ~2.3 km for desert dust cases (AE <

0.35) of winter months, using Eq. 8 with AEC=200 Mm^{-1} (Fig. 4) and AOD=0.45. However *BLH* was 60% smaller than *ALH* in January (1.4±0.3 km) and 35% smaller in February (1.7±0.3 km). *AEC* derived from *AOT* and *BLH* would then be over estimated by 35 to 60%, using the UUAL hypothesis.

In contrary to Ouarzazate, the aerosol layer was not homogeneous for desert dust cases of winter month (Nov-March) of the Sahel region (Fig. 4). Measurements were made at M'Bour (Senegal) which lies into the same region (Sahel) as Banizoumbou [8]. Clearly a local minimum around few hundreds meters shows two distinct aerosol layers: the surface layer below, and a highest layer with a maximum of *AEC* at around 1.0 km a.s.l. (Fig. 4). Moreover the top of the highest layer is not precisely defined as the extinction coefficient decreased from around 200 Mm^{-1} down to 0 within several km. Also, large temporal variability was observed, from 50 Mm^{-1} at few hundreds meters a.s.l. to 450 Mm^{-1} at 1 km a.s.l.. In such vertical profile conditions, measurements, as made by the Cloud-Aerosol LIdar by Orthogonal Polarization (CALIOP) instrument onboard the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) platform, could replace the ECMWF operational analysis products.

ATTENUATION OF THE SOLAR RADIATION AT OUARZAZATE

The attenuation at surface level due to aerosols at Ouarzazate is computed at 500 nm according to Eq. 3 and 10. The increase of *AOT* by desert dust events was partly compensated by the simultaneous increase of *BLH*. *BLH* underwent an important annual cycle at Ouarzazate. *BLH* at 15:00 varied from less than 1.5 km in December 2012-2014 to 4-5 km in July-August 2012-2014. The inter-annual variability can also be significant, e.g. in July *BLH* at 15:00 was 5.0 km in 2013 and 4.3 km in 2014.

The mean value and the variability of the attenuation in Ouarzazate were both significant. The annual mean was 3.7% in 2013 and 5.4% in 2014. The increase of the attenuation from 2 to 6% in winter to 5 to 10% in summer (Fig. 5) was caused by desert dust events. The attenuation was larger in 2014 than in 2013 because the desert dust season was longer and more intense. The attenuation was especially large in December 2013 because of combined increase in *AOT* and decrease in *BLH*. The total transmittance (Eq. 2) at 500 nm could be computed, with T_{gas} = 1.0 and a Rayleigh transmittance of 98.5% at Ouarzazate.

The uncertainty on AOT is 0.01-0.02 [4], which is less than 40% in winter and less than 10% in summer. The uncertainty on *BLH* can vary between 10 and 100% for different methods [13], and can be smaller than 20% for deeper boundary layers [14] which occur at Ouarzazate. We may consequently assume an uncertainty of 50% on *AEC* in winter, a consequently uncertainty smaller than 50% on attenuation in winter, and an uncertainty smaller than 30% on *AEC* and attenuation in summer, integrating the uncertainty due to the UUAL hypothesis. As perspectives, computations have to be made in broadband solar spectrum to compare with previous results [3].

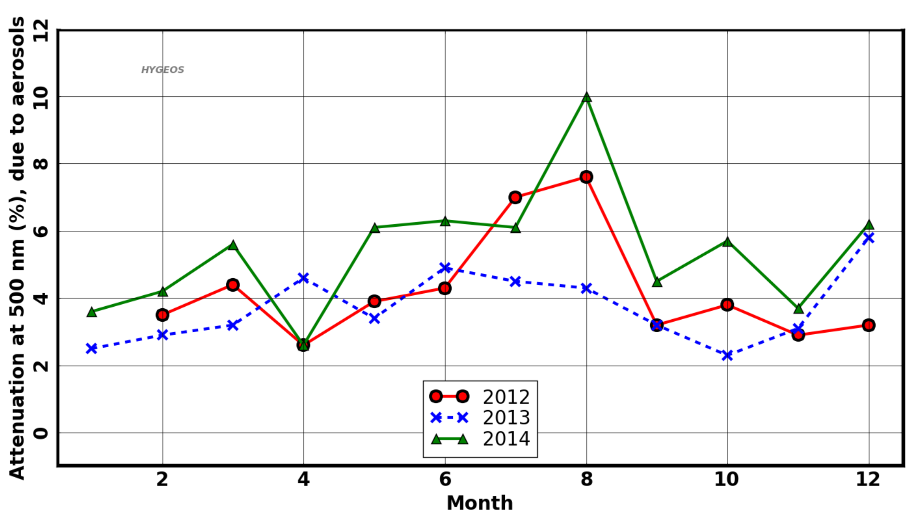

FIGURE 5. Attenuation at surface level in Ouarzazate, at 500 nm and for a distance of 1 km, caused by air molecules and aerosols. Monthly averages were computed for 2012/02-2014/10.

CONCLUSION

We used the aerosol optical thickness measured at an AERONET station and the boundary layer height delivered by the ECMWF operational analysis to estimate the aerosol impact on the transmittance/attenuation of the solar radiation at surface level at Ouarzazate (Morocco). High variability in aerosol amount and in vertical layering generated a significant magnitude in the annual cycle of the aerosol attenuation, and significant inter-annual changes. Indeed while the annual mean of the aerosol attenuation at 500 nm was 3.7% in 2013, a longest desert dust season in 2014 generated an aerosol attenuation of 5.4%. The minimum attenuation of less than 3% was observed in winter and the maximum of more than 7% was observed in summer.

As perspectives, at least one year of ground-based measurements of the aerosol extinction coefficient (made by a nephelometer or a visibilimeter) is necessary to perform a thorough validation of the method. Moreover the variability of the incident solar radiation generated by aerosols could be compared to the variability of the effective electricity production of a running STP. Special care must be taken for sites not respecting the hypothesis of a unique and uniform aerosol layer. Indeed we show that the method would over estimate the aerosol attenuation at surface level at Banizoumbou (Niger) in the Sahel region.

Archives of regional maps of the attenuation by aerosols could be delivered with the presented method, by replacing local observation of *AOT* with spatialised observation by satellite instruments. In particular, the Cloud-Aerosol LIdar by Orthogonal Polarization (CALIOP) onboard the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite platform can provide both the *AOT* and the aerosol vertical layering.

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