



Atmospheric
extinction in solar
tower plants

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Atmospheric extinction in solar tower plants: the Absorption and Broadband Correction for MOR measurements

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Abstract

Losses of reflected Direct Normal Irradiance due to atmospheric extinction in concentrating solar tower plants can vary significantly with site and time. The losses of the direct normal irradiance between the heliostat field and receiver in a solar tower plant are mainly caused by atmospheric scattering and absorption by aerosol and water vapor concentration in the atmospheric boundary layer. Due to a high aerosol particle number, radiation losses can be significantly larger in desert environments compared to the standard atmospheric conditions which are usually considered in raytracing or plant optimization tools. Information about on-site atmospheric extinction is only rarely available. To measure these radiation losses, two different commercially available instruments were tested and more than 19 months of measurements were collected at the Plataforma Solar de Almería and compared. Both instruments are primarily used to determine the meteorological optical range (MOR). The Vaisala FS11 scatterometer is based on a monochromatic near-infrared light source emission and measures the strength of scattering processes in a small air volume mainly caused by aerosol particles. The Optec LPV4 long-path visibility transmissometer determines the monochromatic attenuation between a light-emitting diode (LED) light source at 532 nm and a receiver and therefore also accounts for absorption processes. As the broadband solar attenuation is of interest for solar resource assessment for Concentrating Solar Power (CSP), a correction procedure for these two instruments is developed and tested. This procedure includes a spectral correction of both instruments from monochromatic to broadband attenuation. That means the attenuation is corrected for the actual, time-dependent by the collector reflected solar spectrum. Further, an absorption correction for the Vaisala FS11 scatterometer is implemented. To optimize the Absorption and Broadband Correction (ABC) procedure, additional measurement input of a nearby sun photometer is used to enhance on-site atmospheric assumptions for description of the atmosphere in the algorithm. Comparing both uncorrected and spectral- and absorption-corrected extinction data from one year measurements at the Plataforma

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Solar de Almería, the mean difference between the scatterometer and the transmissometer is reduced from 4.4 to 0.6 %. Applying the ABC procedure without the usage of additional input data from a sun photometer still reduces the difference between both sensors to about 0.8 %. Applying an expert guess assuming a standard aerosol profile for continental regions instead of additional sun photometer input results in a mean difference of 0.81 %. Therefore, applying this new correction method, both instruments can now be utilized to determine the solar broadband extinction in tower plants sufficiently accurate.

1 Introduction

One promising point-focusing solar-thermal technology is the solar tower plant technology. In contrary to linear-focusing systems, e.g. parabolic trough plants, a concentrator (in the case of tower plants called heliostat) is focusing the reflected solar irradiance onto a receiver on the top of a tower. A heliostat field consisting of many heliostats can therefore achieve high temperatures at the surface of the receiver due to the high resulting concentration factor. The direct normal irradiance (DNI) which is the important parameter for Concentrating Solar Power (CSP) plants is one part of the incoming solar radiation reaching the Earth's surface. It is known that the "sun belt" region is displaying high potential for CSP plant technologies due to the high DNI resources available. Large parts of this area are in semi-arid or arid conditions, like the largest desert of the world, the African Sahara. It is the primary source for mineral dust aerosol particles (Washington et al., 2003) and next to sea salt particles, mineral dust has a considerable contribution to atmospheric aerosol (D'Almeida and Schütz, 1983). Atmospheric aerosol extinction can lower the DNI reaching the surface by up to 30 % (Gueymard, 2003). Especially in the lowest hundreds of meters of the Earth's atmosphere higher loads of aerosol particles like mineral dust or e.g. sea salt can be expected. This might be a crucial factor for solar tower plants. The solar radiation which is reflected by the heliostats to the receiver at the top of the tower has to travel a second time through the

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lowest atmospheric layers and this distance might be up to a few kilometers (depending on the solar field size). Therefore, the extinction has to be accounted for in solar resource assessment as well as plant optimization.

State of the art in tower plant models (which are both used for plant yield assessment and plant optimization) is that atmospheric extinction is modeled for standard atmospheric conditions. Some tools provide a choice of different attenuation conditions (Schwarzbözl et al., 2009; Belhomme et al., 2009; Buck, 2011; Kistler, 1986). For example in the DELSOL software by Kistler (1986) the default clear day with low aerosol and humidity load results in 10 % DNI attenuation for a slant range (distance between heliostat and receiver) of 1 km (further denoted with $T_{1\text{ km}}$) and 25 % on a hazy day. Even if some tools recently allow user-defined extinction input to provide eventually more accurate power output calculation, usually missing information about on-site extinction conditions is the main problem and the challenge plant operators are facing.

There are several models developed to determine DNI attenuation and atmospheric extinction in the lowest layer of the atmosphere. The model of Sengupta and Wagner (2012) is based on on-site DNI ground measurements to estimate the AOD (aerosol optical depth) in the lowest atmospheric layers. Attenuation between a heliostat and a receiver is estimated only from these measurements. This approach is already implemented in the simulation tool named SoFiA (Solar Field Assessment for Central Receiver Systems) presented by Gertig et al. (2013). Tahboub et al. (2012) presented the “Swaihan Experiment” consisting of pyrheliometers in different distances to a heliostat and also the “Jebel Hafeet Experiment” in UAE (United Arab Emirates) which utilizes pyrheliometers located at different altitudes at the Jebel Hafeet mountain. The Pitman and Vant-Hull transmittance model (Pitman and Vant-Hull, 1982) was developed on the basis of a dataset by Vittitoe and Biggs (1978). The software tool for layout and optimization of heliostat fields HFLCAL (Schwarzbözl et al., 2009) also provides in addition to the different attenuation levels the utilization of the Pitman and Vant-Hull model. It determines the atmospheric extinction in solar tower plants including 12 different specific atmospheric conditions, using standard atmospheres and assuming exponential

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decrease of air and aerosol density with height. For these reasons the model might not be representative for other atmospheric situations (e.g. low level haze). Nevertheless, additional input of meteorological optical range (MOR) and water vapor measurements in the Pitman and Vant-Hull model might improve the performance of raytracing tools significantly (Hanrieder et al., 2012).

Due to the limited knowledge about suitable sensors to measure the atmospheric extinction, Hanrieder et al. (2012) investigated different commercially available instruments and proposed one scatterometer of Vaisala (FS11) and one long-path visibility transmissometer of Optec (LPV4). To measure the MOR and therefore indirectly the transmittance (see Sect. 2.1), the scatterometer and the transmissometer have been chosen to perform continuous measurement at the Plataforma Solar de Almería (PSA) for more than 19 months. A dataset of one complete year (May 2013 to May 2014) is intercompared and analysed. Both instruments are measuring the MOR at one wavelength and are suitable for usage for on-site ground measurements. In both instruments the MOR is derived from extinction or scattering of monochromatic light. As the current reflected solar spectral transmittance (broadband transmittance) is the relevant parameter for CSP and the solar spectrum shows a considerable diurnal cycle and is also dependent on current aerosol conditions, a narrowband-to-broadband conversion has to be applied on the raw measurements of both sensors (Sect. 2.3.4). The instruments are further not equally considering the absorption (e.g. by water vapor) and scatter effects (Sect. 2.3.3). This has to be kept in mind if e.g. MOR measurements are feed into the Pitman and Vant-Hull model and therefore it also has to be corrected to receive a satisfying corrected measurement result. After applying the here presented correction procedure, both sensor measurements provide valuable input to CSP tools to significantly improve solar resource assessment.

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2 Methodology

2.1 Measurements

Atmospheric extinction is caused by absorption and scattering. Aerosol particles and water vapor have an important influence on the extinction. A beam of incident light is partly attenuated while travelling through an atmospheric layer and parts are transmitted. The Beer-Lambert-Bouguer law describes the monochromatic transmittance introducing the spectral extinction coefficient $\beta_{\text{ext},\lambda}$:

$$T(\lambda, x) = \frac{\text{DNI}(\lambda, x)}{\text{DNI}(\lambda, 0)} = e^{-\beta_{\text{ext},\lambda} x} \quad (1)$$

where $\text{DNI}(\lambda, 0)$ is the incoming spectral DNI at wavelength λ and $\text{DNI}(\lambda, x)$ the spectral DNI after transmittance through a medium after a distance of x .

Atmospheric extinction is lowering the “visibility” which is often reported for traffic or aviation purposes. An exact knowledge about visibility is of importance for safety reasons. There are several definitions to describe the visibility in a distinct atmospheric condition (Gueymard, 2001). Usually visibility is referred to the definition by a human observer and therefore only a rough estimate. Another option to define the visibility is the MOR. The MOR is defined as the length of the path in the atmosphere which is required to reduce the luminous flux in a collimated beam from an incandescent lamp, at a color temperature of 2700 K, to 5 % of its original value (Griggs et al., 1989). Visual range (VR), another parameter to describe visibility, is defined similar but with a 2 % threshold. Following the Koschmieder approximation (Koschmieder, 1924) which is connecting the VR with β_{ext} at 550 nm ($\beta_{\text{ext},550}$) neglecting the spectral variation of the extinction coefficient, MOR can be approximated as follows:

$$\text{MOR} \approx \frac{-\ln(0.05)}{\beta_{\text{ext},550}} \approx \frac{3}{\beta_{\text{ext},550}} \quad (2)$$

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2.1.1 FS11 Vaisala scatterometer

The Vaisala FS11 scatterometer is a commercially available instrument to measure the MOR (Vaisala, 2010). It consists of a transmitter which transmits via a LED a pulsed near-infrared light beam with a peak wavelength of 875 nm (see Fig. 1, left). A lens is concentrating the beam at a small volume of air and a receiver is detecting the scattered photons in a distinct scatter angle (42°). Both optics are orientated downwards. The MOR measurement range includes 5 m to 75 km. This corresponds to a measurable transmittance for 1 km light path of 0 to 0.961 (see upper limit in Fig. 5). The accuracy in MOR measurement is claimed by the manufacturer to be 10 % up to 10 km and 25 % above. The accuracy in transmittance is claimed to be 3 % for a path length of 1 km. A dirt compensation algorithm is implemented which promises the correction of systematic errors of dust deposition on the instrument: additional infrared LEDs and photodiodes measure the reflectance of the sensor windows from the inside of the sensor housing so that contamination can be detected. After several months of measurements the FS11 scatterometer has been characterized as a robust and compact instrument (Hanrieder et al., 2012). Low maintenance demand due to a small required cleaning frequency (about all 2 to 3 months at PSA), as well as low temperature and wind-sensitivity and low power consumption led to the conclusion that this instrument is suitable to be mounted at remote sites for solar resource assessment. The instrument is measuring the beam attenuation due to scatter processes and is not physically taking absorption e.g. by water vapour into account. Nevertheless, the response of the scatterometer resembles a (visible light band) transmissometer response in the typical range of weather conditions (Vaisala, personal communication per email, 2014). The manufacturer claims that the response of the FS11 has been tested, evaluated and verified with a transmissometer including a visible light band emitter at different locations around the world. Therefore is the absorption effect covered to a certain extent, according to the manufacturer, but strongly absorbing phenomena have not been evaluated. Following the WMO standard (Griggs et al., 1989) and the according MOR def-

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inition, the transmissometer lamp should correspond to a white light beam source with a center wavelength of about 1070 nm. We assume that the scatterometer is therefore calibrated to measurements based on a center wavelength of about 1070 nm.

2.1.2 Optec LPV4 transmissometer

5 The long-path visibility transmissometer LPV4 of Optec (see Fig. 1, center) consists of a transmitter and a receiver unit. Both units can be mounted separately in a distance of up to 20 km. At PSA the transmitter unit was located 485 m south-eastwards to the receiver. The transmitter consists of a pulsed LED lamp which emits a peak wavelength of 532 nm with a bandpass filter of 10 nm bandwidth (OPTEC, 2011). The receiver
10 measures the modulated signal from the transmitter and samples signals at times when the transmitter lamp is off so that both signals can be subtracted. Many thousands of cycles are integrated so that background and turbulence noise is reduced. Therefore, the monochromatic transmittance is measured, which is not only lowered by scattering processes, but also by absorption. Although the peak wavelength of the instrument
15 (532 nm) is located outside the main absorptions bands of water vapor, in the for CSP interesting broadband transmittance, water vapor plays an important role. It also has to be considered that aerosol spectral optical properties are a function of relative humidity (Skupin et al., 2014). The measureable MOR range lies between 458 m and 300 km. This corresponds to a transmittance measurement range of 0.002 to 0.990 for 1 km
20 slant range. For the LPV4 an accuracy of 3 % in transmittance measurement is claimed by the manufacturer. For the chosen distance between transmitter and receiver unit at PSA, this results in an accuracy of around 6 % for transmittances for a 1 km slant range (according to the derivation of Eq. 2).

2.1.3 CIMEL sun photometer/AERONET

25 The correction procedure (described in Sect. 2.3) is performed by including additional atmospheric on-site information. To do so, the measurements of PSA's AERONET sta-

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tion (Aerosol Robotic NETwork) are used. The AERONET consists of ground-based sun photometer measurements (Holben et al., 1998) (see Fig. 1, right) and includes currently more than 600 stations worldwide. PSA's datasets are freely available at <http://aeronet.gsfc.nasa.gov> since February 2011 under the name Tabernas_PSA-DLR. Beside AOD (Aerosol Optical Depth) measurements at 8 different wavelengths between 340 and 1020 nm, also total water vapor is provided. Ångström parameters can be derived from the spectral AOD information. Data is available in three quality levels. Level 1.5 data, which is utilized in the correction procedure is already automatically cloud screened (Smirnov et al., 2000).

2.2 Radiative transfer model libRadtran

Radiative transfer simulations in conjunction with the correction procedure are performed with the radiative transfer code libRadtran (library for Radiative transfer) (Mayer and Kylling, 2005). The code is available via <http://libradtran.org>. Direct and global spectral irradiances in the desired height level can be simulated. For all simulations described in Sect. 2.3, following adjustments are made: the spectral range of the simulation was chosen to be between 250 and 4000 nm with a resolution of 1 nm. As radiative transfer solver, *disort* (discrete ordinate method) (Stamnes et al., 1988, 2000; Buras et al., 2011) was chosen as it is the default and recommended discrete ordinate code by the developers (Mayer et al., 2014). A pseudospherical geometry was invoked to account for spherical effects. 16 streams were used to solve the radiative transfer equation. The distribution libRadtran 2.0-beta was used to take advantage of the newly developed gas absorption parameterization REPTRAN (Gasteiger et al., 2014) which is based on HITRAN molecular absorption data. The utilization of the REPTRAN parameterization is available in three different resolutions (fine: band width = 1 cm^{-1} , medium and coarse 5 and 15 cm^{-1} , respectively). REPTRAN medium reduces the computational time noticeable for the purpose of the Absorption and Broadband Correction (ABC) procedure (see Sect. 2.3) but still provides the same band width resolution as

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formerly used correlated-k approximation LOWTRAN (Ricchiazzi et al., 1998) and is based on the even more precise HITRAN data.

Additionally, information about different atmospheric properties as the spectral AOD, ozone column and water vapor content can be included. Also, molecular or aerosol absorption or scattering can be switched off separately which is of special interest for the absorption correction (see Sects. 2.3.2 and 2.3.3).

2.3 ABC – Absorption and Broadband Correction

The ABC (Absorption and Broadband Correction) for visibility measurements focusses on the one hand on correcting the described FS11 Vaisala scatterometer measurement (details in Sect. 2.1.1) for missing consideration of the absorption. On the other hand it translates the monochromatic measurement of both, the scatterometer and the Optec LPV4 transmissometer (described in Sect. 2.1.2), into broadband transmittance which is the important parameter for CSP. The correction algorithm is a two-step procedure.

2.3.1 Atmospheric transmission from sun to heliostat

In a first step, a radiative transfer (RT) through the atmospheric column is performed with libRadtran (see Sect. 2.2). Gas profiles are adopted by the AFGL mid-latitude standard atmospheres by Anderson et al. (1986) chosen dependent on season and scaled linearly by on-site measurements: the ambient ground temperature (T_{amb}), pressure (p) and relative humidity (RH) are taken from a meteorological stations at the site. The standard aerosol vertical profile by Shettle (1989) which is defined by a rural aerosol type in the boundary layer and background aerosol above 2 km height with a ground visibility of 50 km serves as the default setting. Additional information about longitude, latitude, altitude, the precipitable water vapor content, the spectral AOD for 500 nm, the derived Ångström parameters and column ozone concentration by the nearby AERONET station is scaling the default profiles by Shettle (1989) in the case described in Sect. 3.1. In Sect. 3.2 the default aerosol profile of Shettle (1989) without

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any further scaling by AERONET measurement is used. In Sect. 3.3 a standard aerosol profile for an average continental condition is chosen as an expert guess of the aerosol distribution at PSA. The resulting radiation spectrum conduces as external, incoming radiation in the second step of the procedure.

2.3.2 Atmospheric transmission between heliostat and receiver

A homogeneous layer of 1 km depth is defined utilizing ground measurements of T_{amb} , ρ and RH. 1 km is chosen as this is a realistic distance between a heliostat and the receiver in a solar tower plant e.g. GEMAsolar (Torresol, 2014), PS20 (Abengoa, 2014) or IVANPAH (Brightsource, 2014). Other unknown parameters like the O_2 , O_3 , CO_2 densities are adopted, dependent on season and altitude, from the mid-latitude standard atmospheres from Anderson et al. (1986). A second radiative transfer simulation (B1. in Fig. 2) is conducted through this layer using the spectral radiation output from step 1 as initial spectral distribution. The spectral and broadband transmittance for this layer can be calculated from the transmitted DNI spectrum. In a third radiative transfer calculation (B2. in Fig. 2), the parameters are used but the molecular and aerosol absorption effect is neglected.

2.3.3 Absorption correction

Atmospheric extinction is on the one hand caused by scattering and on the other hand by absorption processes by molecules and particles. The FS11 Vaisala scatterometer is considering the scatter contribution in its measurement but only partly the absorption (see Sect. 2.1.1). To model the distinct contributions of both effects, the second step of the correction procedure consists of radiative transfer calculations with (B1. in Fig. 2) and without (B2. in Fig. 2) including radiation attenuation caused by molecular and aerosol absorption.

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Model results for each time step can be translated into a correction factor for the FS11 Vaisala scatterometer for the absorption effect $FA_{1\text{ km,FS11}}$ (C. in Fig. 2):

$$FA_{1\text{ km,FS11}}(t) = \frac{T_{1\text{ km,bb,sca+abs}}(t)}{T_{1\text{ km,bb,sca}}(t)} \quad (3)$$

where $T_{1\text{ km,bb,sca+abs}}(t)$ is the modeled broadband transmittance for 1 km slant range considering scattering and absorption processes, $T_{1\text{ km,bb,sca}}(t)$ is the modeled broadband transmittance only taken scattering into account and $FA_{1\text{ km,FS11}}(t)$ is the resulting factor for absorption contribution to atmospheric extinction for the FS11 scatterometer.

To take the fact into account that absorption is partly resembled in the FS11 measurement due to the calibration with a transmissometer, the mean modeled absorption contribution is calculated and the measurement signal is only corrected for deviations from this average:

$$CFA_{1\text{ km,FS11}}(t) = \frac{FA_{1\text{ km,FS11}}(t)}{FA_{1\text{ km,FS11}}(t)} \quad (4)$$

where $CFA_{1\text{ km,FS11}}(t)$ is the absorption correction factor which is applied to the FS11 transmittance measurement signal (see Sect. 2.3.5).

The difference in broadband transmittance with and without taking absorption into account is displayed in Fig. 3 for 29 May 2013, 12:00:00 UTC. According to the sun photometer, an AOD for 500 nm of 0.05 was measured. In this case, absorption processes account for more than 6% of irradiance attenuation ($T_{1\text{ km,bb,sca}} - T_{1\text{ km,bb,sca+abs}} = 0.0608$). This value varies with site and time and therefore an according time dependent correction factor has to be modeled.

2.3.4 Broadband correction

Both instruments, the scatterometer and the transmissometer, are based on nearly monochromatic measurements (875 and 532 nm, respectively). Figure 3 shows the

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spectral dependency of atmospheric transmittance for 29 May 2013, 12:00:00 UTC. This example model result shows an about 3.4 % higher transmittance for 875 nm compared to 532 nm. As transmittance is spectrally dependent and for CSP broadband transmittance is of interest, this effect has to be corrected. To derive the correction factors for the spectrum and for each instrument, following ratio is calculated (D. in Fig. 2):

$$\text{CFB}_{1\text{ km, sensor}}(t) = \frac{T_{1\text{ km, bb}}(t)}{T_{1\text{ km, sensor}}(t)} \quad (5)$$

In the case of the FS11, $T_{1\text{ km, sensor}}(t)$ is the modeled monochromatic transmittance for a slant range of 1 km and 1070 nm (the wavelength we assume the FS11 is calibrated for). For the LPV4, $T_{1\text{ km, sensor}}(t)$ is the mean modeled monochromatic transmittance for a slant range of 1 km and the wavelength range of 532 ± 10 nm (according to the specifications of the instrument). $T_{1\text{ km, bb}}(t)$ describes the modeled broadband transmittance and $\text{CFB}_{1\text{ km, sensor}}(t)$ is the correction factor for the spectrum which has to be applied to the according transmittance measurements of timestamp t and the sensor.

2.3.5 Final correction

The above described factors result in a final Absorption and Spectral Correction (ABC) for each instrument (E in Fig. 2):

$$T_{1\text{ km, cor, LPV4}}(t) = T_{1\text{ km, LPV4}}(t) \cdot \text{CFB}_{1\text{ km, LPV4}}(t) \quad (6)$$

$$T_{1\text{ km, cor, FS11}}(t) = T_{1\text{ km, FS11}}(t) \cdot \text{CFA}_{1\text{ km, FS11}}(t) \cdot \text{CFB}_{1\text{ km, FS11}}(t) \quad (7)$$

Figure 4 shows the average correction factors $\text{CFB}_{1\text{ km, LPV4}}$, $\text{CFA}_{1\text{ km, FS11}}$ and $\text{CFB}_{1\text{ km, FS11}}$ for the ABC procedure discussed in Sect. 3.1. The mean correction factors are displayed dependent on solar zenith angle (sunrise until solar noon to the left and solar noon until sunset to the right). While the LPV4 is corrected with a factor ($\text{CFB}_{1\text{ km, LPV4}}$) in between 0.98 and 1.02, the FS11 is corrected with factors between 0.93 and 0.99 ($\text{CFA}_{1\text{ km, FS11}} \cdot \text{CFB}_{1\text{ km, FS11}}$).

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3 Results and discussion

Measurement data of the FS11 scatterometer as well as the LPV4 transmissometer from May 2013 to May 2014 are analysed. MOR measurements are averaged to a time resolution of 10 min. Corresponding correction factors are modeled with a resolution of 1 h, linearly interpolated to 10 min resolution and applied to the raw data. For better comparison, measurements of MOR are translated into transmittances for a slant range of 1 km ($T_{1\text{ km}}$) (see Eq. (1) and Eq. 2). Measurement data cover 35 700 data points which corresponds to almost 248 complete days. Other data points were excluded from the analysis because of sensor cleaning or other documented disturbances. Not regarding measurements which have been conducted during night, early mornings or evenings (solar zenith angles $> 85^\circ$) result in 14 943 available data points to be corrected for the time period from May 2013 to May 2014. Simulations for solar zenith angles larger than 85° are not conducted as those time periods are not of interest for CSP plant operators. Therefore the modeled correction factors are limited to smaller angles (see Fig. 5). Figure 5 shows the intercomparison of the FS11 and the LPV4 transmittance measurement. Mean deviation between both sensor measurements accounts for about 4.42 % with a SD of 11.43 %.

Outlier data points for which the transmittance measured by the FS11 is exceeding the LPV4 measurement might be explained by local disturbances. While the FS11 is located in the Northeast of the PSA, the LPV4 is mounted in the South. Additionally, the distance between transmitter and receiver unit and therefore the sampled air volume is small for the FS11 compared to the LPV4 which is mounted with a horizontal distance of about 485 m between the transmitter and the receiver. The LPV4 is therefore also more sensitive to local disturbances as for example dust plumes being transported through the sampled air volume by passing by cars.

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3.1 Absorption and Broadband Correction with information about on-site aerosol conditions

This presented ABC procedure is utilizing on-site measurements of T_{amb} , ρ , RH by a meteorological measurement station. Additionally, information about the spectral AOD as well as ozone and water vapor column concentration measured by the near-by CIMEL sun photometer is included to optimize the correction results and to display the on-site aerosol conditions as good as possible.

The result of the ABC procedure applied to the raw transmittance measurements from Fig. 5 is shown in Fig. 6. The mean difference between the corrected FS11 and the corrected LPV4 signal is reduced by a factor of 7.65 to 0.58 %. The mean SD between both corrected datasets is virtually the same (11.43 vs. 11.40 %).

While the average uncorrected transmittance for 1 km slant range monitored by the FS11 scatterometer is 94.50 %, the LPV4 transmissometer measures a mean uncorrected transmittance $T_{1\text{km}}$ of 90.08 % (for solar zenith angles $< 85^\circ$). After correction of the 14 943 data points, the average transmittances account to 90.03 and 89.45 %, respectively (see Table 1). Outlier data points which display lower transmittances derived from the FS11 measurements compared to the LPV4 measurement can be explained by the different sensitivity of the instruments to local disturbances as explained earlier.

The monochromatic measuring instrument LPV4 works with a band pass filter of about 10 nm in the visible spectral region. Therefore, main absorption bands (e.g. of water vapor) will not be considered and will not reduce the measurement signal (see also example in Fig. 3). But this reduction plays an important role in the for CSP interesting broadband transmittance. Hence, the effect of spectrally correcting the raw LPV4 signal to lower transmittances by about 0.63 % is compensating this systematic error due to absorption. The same is also true for the spectral correction of the FS11 scatterometer while here an additional factor, the lack of information about absorption which is also corrected, is added.

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3.2 Absorption and Broadband Correction for a non-site specific standard atmosphere

Unlike in Sect. 3.1, in this evaluation no information from the near-by CIMEL sun photometer is included in the first step of the ABC procedure which is the simulation the transmission between the sun and the heliostat. As sun photometer data might not be available on every site of interest and according demanded solar resource assessment, this section presents the results conducted with the ABC procedure without considering on-site sun photometer measurements. Precipitable water vapor content, the spectral AOD for 500 nm and column ozone concentration are defined by the chosen AFGL mid-latitude standard atmospheres by Anderson et al. (1986) and the standard aerosol profile by Shettle (1989). T_{amb} , ρ and RH are still taken from on-site measurements.

Figure 7 displays the corrected transmittance for a slant range of 1 km and measured with the FS11 scatterometer and the LPV4 transmissometer. Noticeable is the higher mean difference between both corrected signals (0.806 %) compared to the results presented in Sect. 3.1 (0.58 %, respectively). The difference between both sensors is reduced by a factor of about 5.48 in comparison to the raw data mean difference. The mean SD (11.46 %) is about the same as for the raw data without correction.

After the correction without the additional input of AERONET data, a mean $T_{1\text{ km}}$ of 90.27 % can be calculated for the FS11 while the LPV4 shows a mean value of 89.46 % (see Table 1).

This findings show that the application of the ABC procedure without additional AERONET input also results in satisfying coincidence between both corrected datasets and a better agreement by a factor of about 5.48. The mean small difference between average $T_{1\text{ km}}$ with and without additional input of AERONET data indicates that the default aerosol composition and profile defined by Shettle (1989) which is utilized instead of exploiting the AERONET information is not fitting perfectly the on-site situation at PSA. Nevertheless this standard profile is describing the on-site aerosol situation quite well. This only accounts for PSA and might not be the case for other sites.

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3.3 Absorption and Broadband Correction using an expert guess aerosol type

The default setting of libRadtran for the aerosol profile according to Shettle (1989) fits quite well the situation at PSA what can be seen in Sect. 3.2. As this might not be the case for other sites, an expert guess can be applied which includes assumptions about most probable aerosol type contribution and height distribution for the site to enhance the performance of the ABC procedure without additional AERONET measurements. Therefore, further evaluation of the ABC procedure is conducted by customizing the aerosol profile: LibRadtran provides typical optical properties of aerosols and their vertical distribution calculated based on refractive indices and size distributions of the software package OPAC (Hess et al., 1998; Emde et al., 2010). Comparing mean Ångström parameters and optical depths of the nearby AERONET station for 2012 and 2013 with the given values for the standard aerosol profiles, the “continental average” aerosol profile displays the best fit to the local conditions. The profile represents remote continental areas and consists mainly of an increased amount of soluble and insoluble aerosol components together with a small soot contribution to describe the anthropogenic influence. Alternatively, also other available datasets which include aerosol information for example from satellite retrievals or regional models can be included to choose a best fitting standard aerosol profile.

Figure 8 displays the corrected transmittance measurements of the scattero- and transmissometer. In comparison to results of the evaluation conducted in Sect. 3.1, a mean difference between both corrected signals of 0.81 % is achieved. This is around 0.023 % higher than the results from Sect. 3.1. The mean SD (11.40 %) is virtually the same as in Sect. 3.1. This result shows a similar coincidence with the results conducted with additional input of sun photometer data compared to the results of Sect. 3.2.

The mean corrected transmittance for the scatterometer and the transmissometer are 89.93 and 89.12 %, respectively. These results indicate that the standard average continental aerosol profile fits similar the actual situation at PSA compared to the standard aerosol profile by Shettle (1989).

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The results show that the ABC procedure improves the coincidence between both instruments even without accessible sun photometer data. In this case, careful selection of assumptions about atmospheric parameters like spectral AOD or water vapor content is recommended.

4 Conclusion and outlook

Atmospheric extinction is a crucial factor in plant yield assessment and plant optimization of solar tower plants. It can vary strongly with site and time. Two commercially available instruments which are measuring indirectly the atmospheric transmittance are selected. These instruments, the Vaisala FS11 scatterometer and the Optec LPV4 transmissometer, are both based on a monochromatic measurement principle. As the solar spectrum undergoes a certain diurnal and annual cycle this must be accounted for due to the spectral dependence of the instruments. The scatterometer is additionally considering the atmospheric absorption only indirectly to a certain extent due to the calibration process and is excluding strongly absorbing phenomena.

A correction method concerning mentioned limitations of these instruments was developed. The Absorption and Broadband Correction (ABC) consist of different radiative transfer calculations conducted with libRadtran (Mayer and Kylling, 2005) to simulate time-dependent spectral transmittance. Additional input of sun photometer data into the procedure is possible. A dataset conducted at the Plataforma Solar de Almería (PSA) spanning measured transmittances data from May 2013 to May 2014 was evaluated.

The ABC procedure including additional information about the atmosphere from sun photometer measurement results in an improved coincidence of the scatterometer and the transmissometer data by a factor of 7.65 (mean difference of raw data: 4.42%, mean difference of data after ABC: 0.58%). Mean monochromatic transmittances for a slant range of 1 km for the whole time period is calculated for the uncorrected data to be 94.50 and 90.08% for the scatterometer and the transmissometer, respectively.

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Applying the ABC procedure lowers the derived mean broadband transmittances to 90.03 and 89.45 %.

As sun photometer data might not be available on every site of interest, the evaluation of the ABC without inputting additional information from a sun photometer was conducted. Depending on the chosen aerosol conditions, it still shows enhanced coincidence (0.806 % for a standard aerosol profile according to Shettle (1989), 0.809 % for the standard average continental aerosol profile according to OPAC (Hess et al., 1998; Emde et al., 2010)) between the two sensors. Therefore, careful selection of assumptions about the atmosphere depending on the site and time is improving the performance of the ABC procedure.

These findings are only valid for PSA. The ABC might result in different correction factors at other sites as the solar spectrum as well as molecular and aerosol absorption conditions will differ. The instruments might over- or underestimate actual atmospheric extinction without the according correction procedure. Therefore it is recommended to apply the ABC also for industrial purposes.

Further investigation about more precise atmospheric parameterization will be performed. Larger datasets and different sites will be evaluated to refine the procedure for global application.

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Table 1. Average transmittance for 1 km slant range before and after ABC.

	No correction	ABC with AERONET data	ABC without AERONET data	ABC with OPAC continental average aerosol profile
$T_{1\text{ km, FS11}}$	94.50 %	90.03 %	90.27 %	89.93 %
$T_{1\text{ km, LPV4}}$	90.08 %	89.45 %	89.46 %	89.12 %

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Figure 1. Left: scatterometer Vaisala FS11, center: long-path transmissometer Optec LPV4, right: sun photometer CIMEL.

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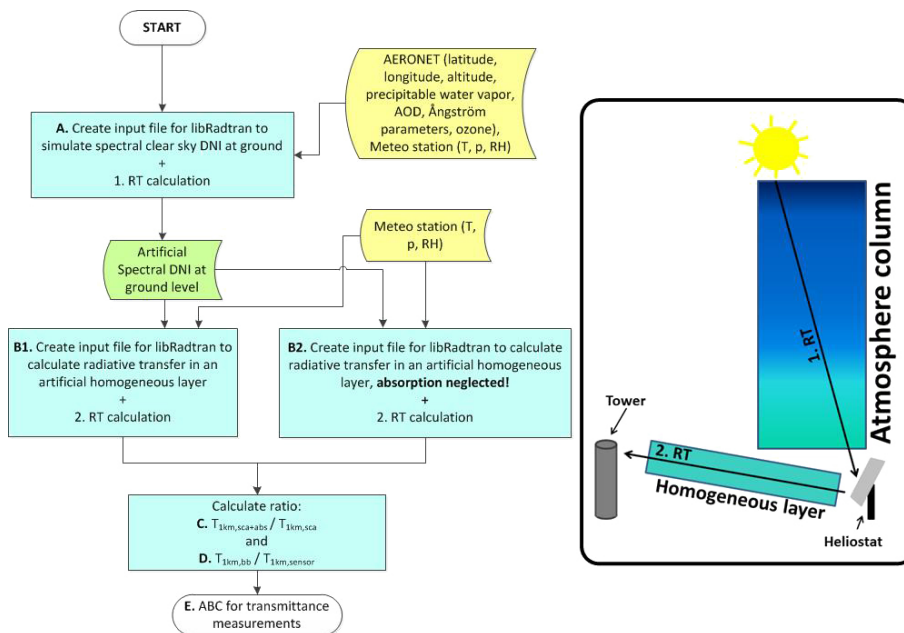


Figure 2. Right: sketch of two stepped correction procedure for spectrum and absorption correction. Left: symbolic sketch of radiative transfer calculations through two layers.

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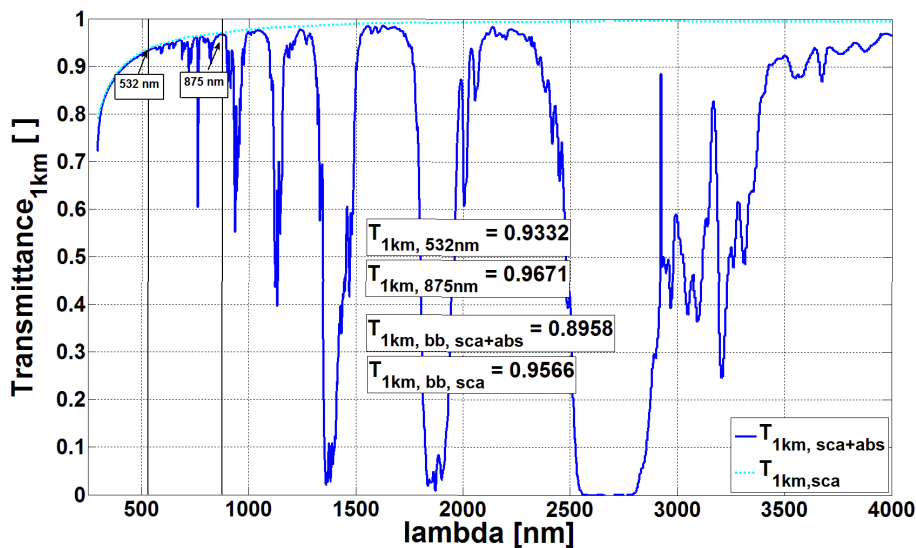


Figure 3. Spectral transmittance (blue, solid line) and spectral transmittance without absorption (cyan, dotted line) for a slant range of 1 km, 29 May 2013, 12:00:00 UTC, PSA. Vertical lines show the location of the LPV4 transmissometer (532 nm) and the FS11 scatterometer (875 nm) measuring wavelengths.

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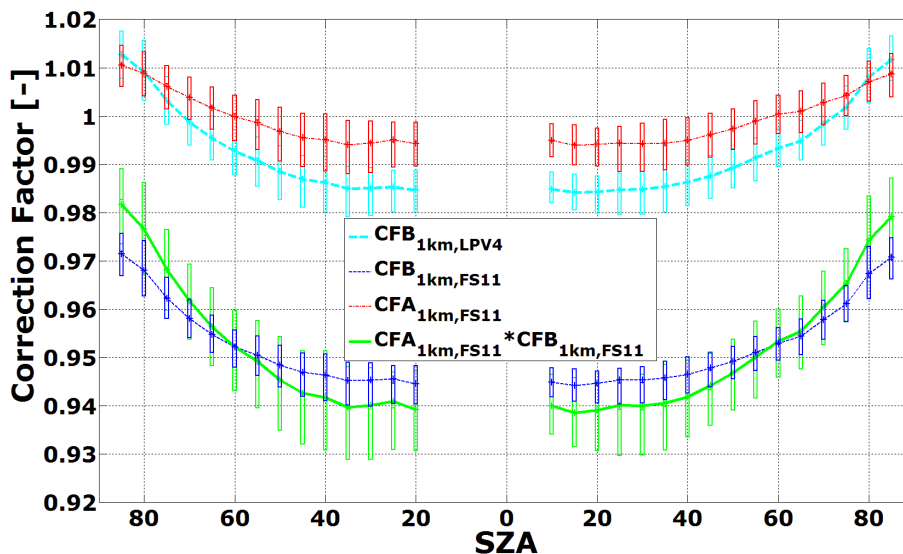


Figure 4. Mean behavior of correction factors (for case described in Sect. 3.1) $CFB_{1\text{km},\text{LPV4}}$ for LPV4, $CFB_{1\text{km},\text{FS11}}$, $CFA_{1\text{km},\text{FS11}}$ and the total correction product $CFA_{1\text{km},\text{FS11}} \cdot CFB_{1\text{km},\text{FS11}}$ for FS11 dependent on SZA. Bars display 68.3% of all data points.

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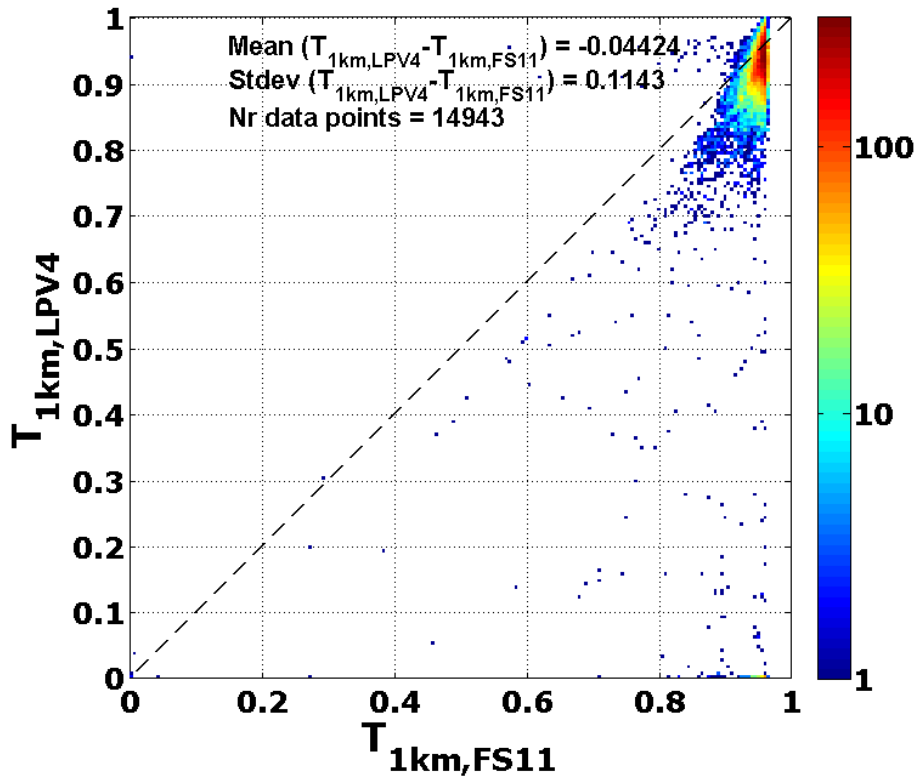


Figure 5. Uncorrected transmittance for 1 km slant range measured by FS11 scatterometer and LPV4 transmissometer without application of the ABC. Time steps with solar zenith angles of more than 85° are excluded. Color distribution displays the number of data points per grid point (logarithmic color scale).

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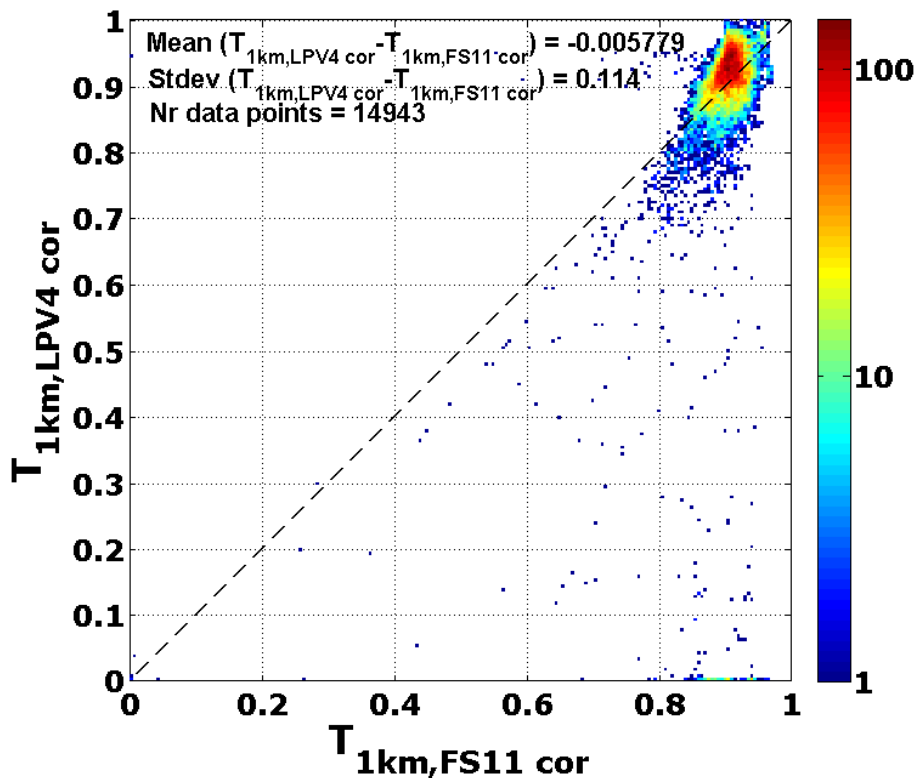


Figure 6. Absorption and broadband corrected transmittance for 1 km slant range measured by FS11 scatterometer and LPV4 transmissometer. Color distribution displays the number of data points per grid point (logarithmic color scale).

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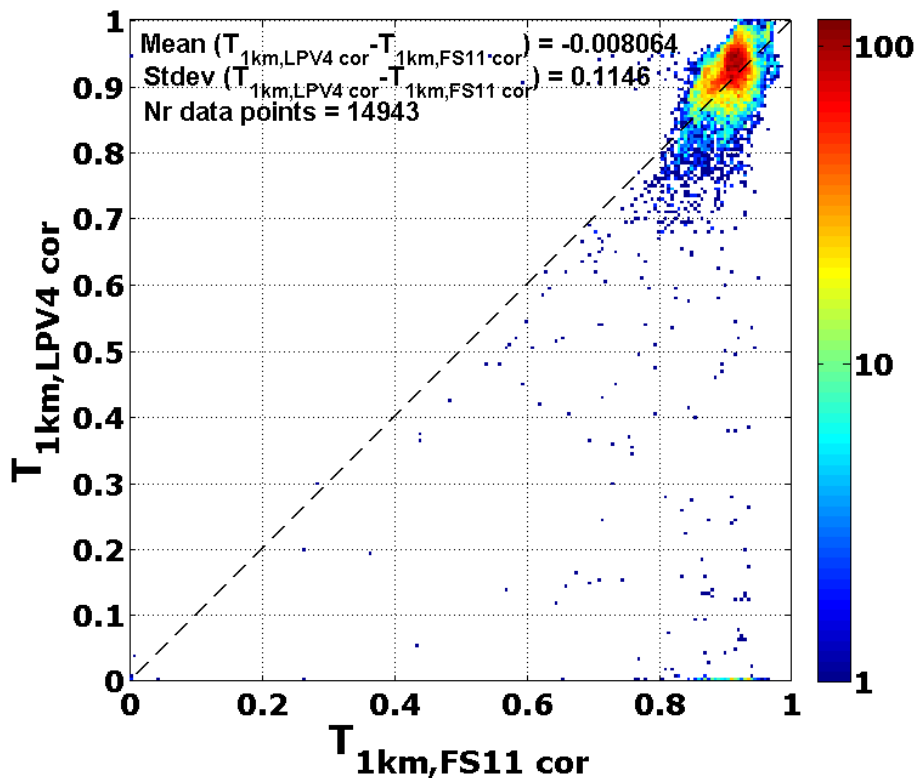


Figure 7. Absorption and broadband corrected transmittance for 1 km slant range measured by FS11 scatterometer and LPV4 transmissometer. No sun photometer input in ABC procedure. Color distribution displays the number of data points per grid point (logarithmic color scale).

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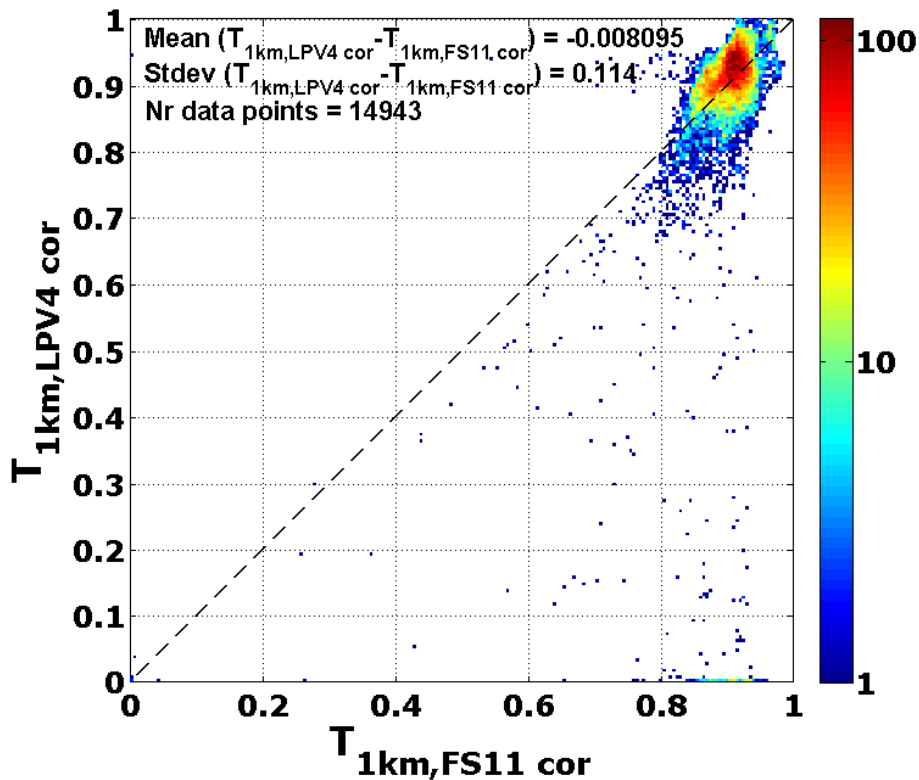


Figure 8. Absorption and broadband corrected transmittance for 1 km slant range measured by FS11 scatterometer and LPV4 transmissometer. Input of standard aerosol profile “continental average” in ABC procedure. Color distribution displays the number of data points per grid point (logarithmic color scale).

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