DETERMINATION OF BEAM ATTENUATION IN TOWER PLANTS

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Abstract

Atmospheric extinction between the heliostat field and receiver in solar tower plants is known to cause significant losses of reflected Direct Normal Irradiance. This phenomenon brings a limitation on the size of the heliostat field and is included in some raytracing and plant optimization tools. Usually, no detailed information about the local meteorological conditions is available for many sites that are now of interest for tower plant projects. Therefore, only standard atmospheric conditions are commonly used to describe the attenuation and also the height profiles of relative humidity and aerosol concentration. First of all the existing models are presented. The use of the Pitman and Vant-Hull model with real measurement data represents an improvement with respect to site independent calculations. Thus different commercially available instruments that can provide the input for the state of the art models are described, tested and intercompared. Also the limitations of the state of the art are discussed and methods to overcome these limitations are shown. The choice of the tested instrumentation and the evaluation of the different instruments have been performed with regard to necessary enhancements. Several months of MOR (Meteorological Optical Range) measurements from the Plataforma Solar de Almería (PSA) are presented. These data provide a base for further evaluation of the investigated instruments. The FS11 scatter meters display satisfying accuracies on transmittance measurements and their robust composition and low sensitivity to soiling facilitate application at remote sites. The Degreane TR 30AC transmissometer is rather suitable for smaller slant ranges than those required for many solar tower plants as uncertainties for clear atmospheric conditions are high. The Optec LPV-4 transmissometer obtains high accuracies for clear conditions if large working path distances are used to exploit the preciseness of the instrument. The presented measurement methods enable improvements in tower plant design and yield analysis, but still enhancements of the existing models are required. The discussed instruments, additional sensors and modeling approaches can be used to develop such methods.

Keywords: beam attenuation, atmospheric extinction, solar tower plants, transmission, visibility, solar resource

1. Introduction

In solar tower plants a considerable part of the solar radiation is attenuated on its way from the heliostats to the receiver. In raytracing software this effect is commonly modeled for one standard atmospheric condition although some programs even allow the specification of various attenuation levels [1, 2]. In [1] the default cases result in 10% attenuation for a slant range of 1 km (beam path between heliostat and receiver) on a clear day and in 25% on a hazy day. Despite of the noticeable influence of this effect, users usually do not have information on the average extinction conditions of investigated plant sites. Also, site specific time series of the attenuation effect would represent an advantage for the layout of solar tower plants and facilitate a decision between tower and trough/fresnel technique where this is an issue.

One approach to determine the extinction in tower plants involves a model derived by Pitman and Vant-Hull [3]. With this model (P&V model), the attenuation for a given slant range can be calculated with further input

of the site altitude, tower height, absolute air humidity and β_s, the scatter coefficient at 550 nm. However, β_s is often not included in solar resource assessment. Also, the model is based on calculations of atmospheric transmission for very specific conditions. It assumes that the aerosol density decreases exponentially with the site altitude and the height over ground. As [3] point out, it does therefore not cover all atmospheric conditions (e.g. low-level haze or situations present close to aerosol sources). However the use of the model with measured input parameters represents a step forward. For more accurate modeling of central receiver plants new height resolved measurements of the extinction coefficient are necessary. For this purpose, different available instruments have been setup and tested at the PSA.

2. Modeling beam attenuation in solar tower plants: Introduction and State of the Art

Absorption and scattering together are attenuating the beam of incident light. This process is called extinction. For monochromic light it is described quantitatively with the Beer-Lambert-Bouguer law involving the extinction coefficient. As the extinction coefficient and its spectral variation is not measured very often, other parameters describing the "visibility" might be used for resource assessment. There are several definitions to describe the "visibility" in a distinct atmospheric condition [4]. Usually visibility, which is often reported at airports, is referred to the definition by a human observer and therefore only a rough estimate. Another option is the Meteorological Optical Range (MOR). It is defined as the length of the path in the atmosphere 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 [5]. The Visual Range (VR) is defined on a similar way but the reduction to 2% is stated. Neglecting the spectral variation of the extinction coefficient, the MOR, the VR and the extinction coefficient β_e at 550 nm can be related using Koschmieder´s approximation [6]:

$$MOR \approx \ln(0.05) / \beta_e \approx 3 / \beta_e \qquad \text{and} \qquad VR \approx \ln(0.02) / \beta_e \approx 3.9 / \beta_e$$

Pitman and Vant-Hull developed a transmittance model to calculate the attenuation of a solar beam propagating between a heliostat and a receiver [3]. The included formulas display functional fits to data of Vittitoe and Biggs [7] which have been calculated by numerical integrations of spectral transmittance data using LOWTRAN 3. As Vittitoe and Biggs chose only two different site elevations H, two model atmospheres (mid-latitude winter and mid-latitude summer) and three distinct aerosol conditions (no aerosol, 5 km and 23 km VR at sea level), an accurate estimate of attenuation loss can only be provided for 12 specific conditions. Including three tower heights h (100 m, 300 m and 882 m) and five slant ranges S (between h and 2000 m) this results in 180 data points. To fit these data points best, ten constants have been set. The model of P&V is wavelength independent and contains *five explicit physical variables*: the atmospheric water vapor density ρ, the scattering coefficient β_s at a wavelength of 550 nm, site elevation H, tower height h and slant range S. Additionally, *three implicit variables* are included: the season of the year, climatic region and site elevation H. These variables are named implicit as ρ and β_s strongly depend on them.

Although the P&V model represents a step forward especially if measured input parameters are utilized to run the model, there are still crucial limitations. One main simplification in this model is that both considered model atmospheres and aerosol conditions assume an exponential decline of air and aerosol density with increasing altitude above sea level. The model was developed to fit data which assumed such height profiles. As the extinction coefficient β_e is calculated based on these atmospheric conditions, its profile shows also an exponential dependence using the model, which is not realistic for most other atmospheric conditions. Current state of the art is the usage of a transmittance model without further input of site and time resolved data of the extinction coefficient. Therefore, many raytracing tools only utilize standard values concerning atmospheric conditions for resource assessment which might not fit the actual situation. In contrast to measuring the extinction coefficient, MOR measurements are common as they are also utilized for example for traffic purposes and there exist commercially available instruments.

Different raytracing tools for solar tower plants include the attenuation between the heliostat and the receiver. The raytracing tool SPRAY [8] is based on the former code MIRVAL developed by Sandia National Laboratories [9]. SPRAY includes two atmospheric options to model attenuation so far. The first corresponds to low humidity and low dust contamination in the air, while the second option is characterized by high humidity. The HFLCAL code (''Heliostats Field Layout CALculations'') [2] models atmospheric attenuation

of rays identically to the MIRVAL code as a function of the slant range S (two different transmission factors for S ≤ 1 km and S > 1 km). Additionally, updates allow specifying the transmittance model either without atmospheric attenuation, for high absorption, with adaptable extinction factor, or for the standard P&V model. DELSOL [1] is considering atmospheric attenuation in the same way as MIRVAL does so that three options are offered: Clear day at Barstow CA USA, VR = 23 km, a hazy day at Barstow CA USA, VR = 5 km or a user defined attenuation. The developed software STRAL [10] is utilizing a simplified model of MIRVAL to calculate beam attenuation between each single heliostat and the receiver depending only on the slant range S. The software package Greenius (Green Energy System Analysis) [11] which is able to perform technical and economical simulations of solar tower power plants also includes beam attenuation as the heliostat field performance is based on HFLCAL [12].

This limited integration of meteorological input parameters in existing raytracing tools motivates further investigation of site- and time resolved determination of beam attenuation. Therefore, a first step at PSA is the examination of different available instruments to enable site specific time series as input for yield analysis and field optimization.

3. Experimental setup

At PSA a selection of available MOR and transmission sensors is mounted and results are intercompared. The selection consists of the following instruments (Fig. 1): Two Vaisala FS11 scatter meters and one FS11P present weather sensor, one Degreane TR 30AC Transmissometer with 75 m baseline and one Optec LPV-4 Long Path Visibility Transmissometer with 486.34 m baseline.
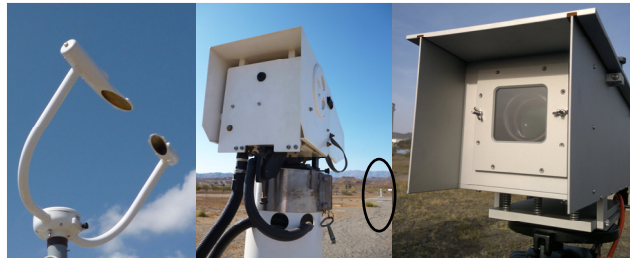
Fig. 1. Sensors at PSA. From left to right: Scatter meter FS11, transmissometer TR 30AC, transmissometer LPV-4 (only transmitter shown).

The instruments have been chosen to provide a diversity of different measurement methods and application possibilities. The Vaisala FS11 scatter meters consider scatter processes in a small air volume and promise applicability at remote sites. The LPV-4 is designed to operate with distances up to 20 km between the transmitter and receiver and additionally a non-horizontal path to measure transmittance is possible. So the receiver can also be mounted on the tower of a solar tower plant which is an advantage for investigation of beam attenuation under such conditions. In contrast to the other two sensors, the white balanced halogen lamp of TR 30AC is providing a beam irradiance spectrum closer to the solar spectrum. In the following the sensors are described in more detail.

3.1. Scatter Meters FS11 and FS11P

The FS11 scatter meter determines MOR based on forward scattering of pulsed light in a small volume of air [13]. Therefore a LED sends a 2.2 kHz pulsed near infrared light beam (peak wavelength 875 nm) through a lens which concentrates the beam to a small volume of air. The scatter measurement angle between transmitter and receiver is 42° and both optics are oriented downwards. The instrument version FS11P is equipped with an additional weather sensor: A precipitation identifier PWD32 for measuring the intensity and type of precipitation and haze. The FS11P determines the current present weather code on the basis of these values, the temperature and the MOR. Uncertainty for MORs is claimed to be 10% between 5 and 10 km and 25% up to 75 km. The FS11 has a contamination compensation for both windows which uses an additional LED and photodiode to indirectly measure the window transmittance and thus the contamination. According to Vaisala the sensor has to be cleaned when the contamination limit is exceeded or at least every

six months [13]. This will be investigated in detail in Section 4. The calibration process took place at the factory and a calibration check is recommended once a year with a calibration kit. This kit consists of zero plugs to block the receiver and transmitter optics to obtain a zero signal and two opaque glass plates to receive a high constant signal. The same calibration set was used to calibrate all three sensors.

3.2. Transmissometer Degreane TR 30AC

The TR 30AC measures at PSA the transmission along a horizontal path of 75 m between a white balanced halogen lamp (400-700 nm, peak at 650 nm) and the receiver unit [14]. A photo diode receives the emitted energy with a frequency of 30 Hz. The beam has an optical beam angle of 1°.The transmissometer measures the emitted and received flux and delivers averaged Transmission Ability of the Atmosphere (TAA) and the MOR. TAA accuracy is maintained as better than 0.75% for 0.15-0.3% TAA values and better than 0.35% above according to the manufacturer. Uncertainty of MOR for 30 m baselength is claimed to be 1% up to 200 m and better than 20% above 3000 m. An auto calibration algorithm is included in the software which should prevent from detecting unusual MORs due to external reflection effects or strong soiling, ageing or misalignment by adjusting the calibration number. It includes as well a compensation for the effect of soiling of the optical parts. To calibrate the TR 30AC transmissometer, a second MOR sensor is required as a reference. At PSA, FS11 scatter meter data are used to calibrate the TR 30AC transmissometer.

3.3. Transmissometer Optec LPV-4

The LPV-4 (Long Path Visibility Transmissometer) [15] uses the same principle of operation as the TR 30AC, but here the receiver can be positioned at a distance up to 20 km from the light source (at PSA a distance of 486.34 m is used so far). The sensor consists of a constant output light source transmitter and a receiver. The LPV-4 also allows the measurement of the transmittance along a non horizontal path between a heliostat and the top of the tower. The transmitter uses a LED lamp with a 532 nm bandpass filter of 10 nm bandwidth. The receiver 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. This difference is integrated over many thousands of cycles so that the receiver can distinguish the transmitter's signal from background and turbulence noise. Visual range and the extinction coefficient are derived. The extinction coefficient can be determined from 0.01 to 6.5535 km^{-1} which corresponds to a MOR ranging from 458 m to 300 km. The specified value for uncertainty of transmittance is 3%. As the working path of 486.34 m is quite short, a neutral density filter (0.0156 transmittance) was placed before the receiver to prevent it from saturation. Additionally, the window transmittance at the receiver and the transmitter housing has to be considered (both 0.896). These windows have been ordered optionally to shield the components from external influences. For calibration the differential path method was chosen as this technique is valid for extinction coefficients that exceed 0.1 km^{-1}. The method calculates the atmospheric extinction between the calibration site (with a distance of 161.89 m to receiver) and the working site (486.34 m distance to receiver) and assumes that the extinction coefficient is constant throughout the entire path between receiver, calibration site and working site. With this extinction coefficient one can calculate the transmission using Beer–Lambert–Bouguer law. The calibration number for the working path length can be calculated as the ratio between the mean raw reading for working path (counts) and the transmittance. Performing the calibration, the transmitter is moved closer to the receiver and 10 consecutive 1-minute integrations are recorded and compared to the same amount of data taken at the original working distance in order to derive the calibration number.

3.4. Complementary instrumentation

The experimental setup is completed by additional sensors for monitoring the water vapor density, direct normal irradiance (DNI) and further related physical parameters. Especially dust monitors measuring the particle size distribution and concentration are of importance [16]. These measure suspended particles in the size range between 0.25 to 32 μm in 31 different size channels. The size distribution is determined via spectrometric measurements of the investigated air volume and derives the size distribution using an internal algorithm that assumes round particles as the scattering centers. Another more cost efficient sensor is the TSI Dusttrak DRX sensor. This sensor does not give a whole size distribution of airborne particles but measures the fine dust parameters PM 1, PM 2.5 and PM 10 simultaneously. These parameters are interesting because many governmental institutions have been measuring them e.g. for health issues so that there exists already a

large database throughout large parts of the world. Further instrumentation installed at the measurement site includes the ultrasonic 3 dimensional Campbell CSAT3 wind sensor and several cup anemometers. Together with the Campbell soil moisture sensor 257-L it can be used for investigations on particle uptake by wind. Hence, a data basis is created for a later parameterization of the extinction based on more easily determinable measurements than MOR or measurements being already taken at a larger scale for different purposes.

4. Experimental results

4.1. Comparison of the investigated sensors

Several months of measurements using 3 FS11 scatter meters have been extended by the comparison to LPV-4 and TR 30AC transmissometers. According to the Koschmieder approximation [6] the connection between MOR and the transmittance τ is as follows: $\tau \approx \exp(-3S / MOR)$. Using this approximation, transmittances for a light path of 1 km have been calculated for each sensor to facilitate the comparison. The exemplary graph in Fig. 2 shows transmittances for the 5 sensors at PSA. The x-axis displays the reference transmittance values of one scatter meter, here FS11-1. On the y-axis transmittances of the other 4 sensors are shown.

Two scatter meters show good agreement (FS11-1 and -2) while the third scatter meter displays a slight bias towards higher τ. Also the spreading of the FS11-3 relative to the FS11-1 is higher than in the case of the FS11-2. In general the FS11 measurements coincident roughly even close to the upper detection limit (75 km).

TR 30AC shows noticeable deviations which are above the specification. Over several hours it detects higher MORs than the FS11-1 (up to its detection limit of 70 km). It is claimed that TR 30AC operates up to external solar radiation of around 1400 W/m^2, but an influence of the solar radiation and the solar position on the deviation to the FS11-1 was found.
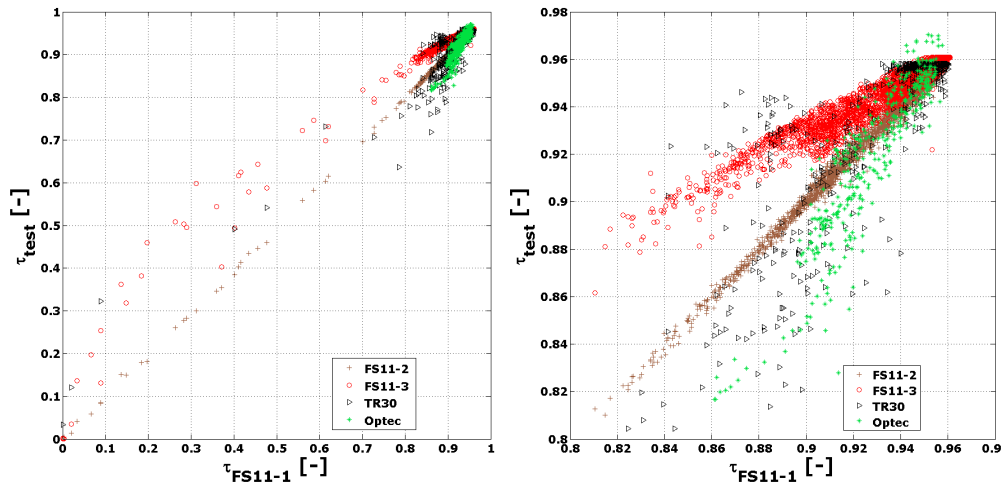
Fig. 2. 10 min mean transmittance of FS11-2 and -3, LPV-4 and TR 30AC vs. reference transmittance of FS11-1. Transmittances are calculated from the MOR for a path of 1 km.

Depending on the used reference, the calibration technique restricts the measurement accuracy by introducing a considerable calibration uncertainty. Its emitted broad spectrum displays nevertheless an advantage compared to monochromatic transmissometers.

The LPV-4 transmissometer shows lower transmittances compared to the FS11-1, but general coincidence can be noted. The instrument is able to deliver higher accuracies for longer working path distances, as discussed below.

For a better comparison of the accuracies of the different instruments, extrapolation of specified values for a fixed slant range is used. For extrapolation of accuracy for a slant range of 1 km, one assumes a constant extinction coefficient. The transmittance and MOR are logarithmically connected. That indicates that measured uncertainties in transmittance result in calculated uncertainties of MOR dependent on slant range S as transmittance depends on S. MOR $\approx$ -3S/ln τ implies that the connection between relative error ΔMOR (in %) and the relative error in measurement of the transmittance $\Delta\tau$ (in %) is as follows:

ΔMOR $\approx$ MOR$^2 \cdot \Delta\tau$ / (S $\cdot$ ln (0.05)).

The accuracy of transmittance for a different slant range can be calculated with $\Delta \tau_2 = S_2/S_1 \cdot \Delta\tau_1$. where S_1 and τ_1 refer to the original working path, while S_2 and τ_2 are related in this case to a path length equal 1 km. Using these formulas, the following uncertainties are obtained:

Uncertainty for the FS11 MOR measurement is claimed to be 10% up to 10 km. This corresponds to a transmittance uncertainty of 3% for a path length of 1 km.

TR 30AC claims uncertainties of 0.35% for transmittance higher than 0.3% and a path length of 30 m. That corresponds to uncertainty of 4.7% of transmittance for a path length of 1 km.

The manufacturer of LPV-4 transmissometer claims uncertainty of transmittance of 3%. Transferring this from the selected working path at PSA (486.34 m) to the uncertainty for a slant range of 1 km results in 6.2% uncertainty. Longer working path lengths can be used to improve the accuracy of the LPV-4 crucially. The instrument can be used with a working path length of up to 20 km between the transmitter and the receiver. This working path length would result in transmittance uncertainty of 0.15% for 1 km slant range.

Assuming a path of 1 km and a MOR of 70 km the following conclusions can be drawn: Relative uncertainties for τ for the FS11 are 70% while TR 30AC shows more than 100%. Therefore, the TR 30AC is not adaptable for application concerning typical slant ranges in tower plants and high MORs. LPV-4 implies as well an uncertainty of more than 100% for the used working path. But if one assumes a working path length of 20 km, an uncertainty of around 3.5% can be expected.

Sensor soiling compensation

Especially due to application on remote sites, sensor soiling should be investigated in detail. The previous uncertainty analysis does not include the aspect of soiling of the instrument. FS11 and TR 30AC have a soiling compensation implemented. TR 30AC is designed to be in operation for example on airport sites, so it should be assured that sensor soiling does not affect MOR output and therefore the estimation of air safety. As FS11 might be put up at remote sites, the following investigation on FS11 sensor soiling has been made.
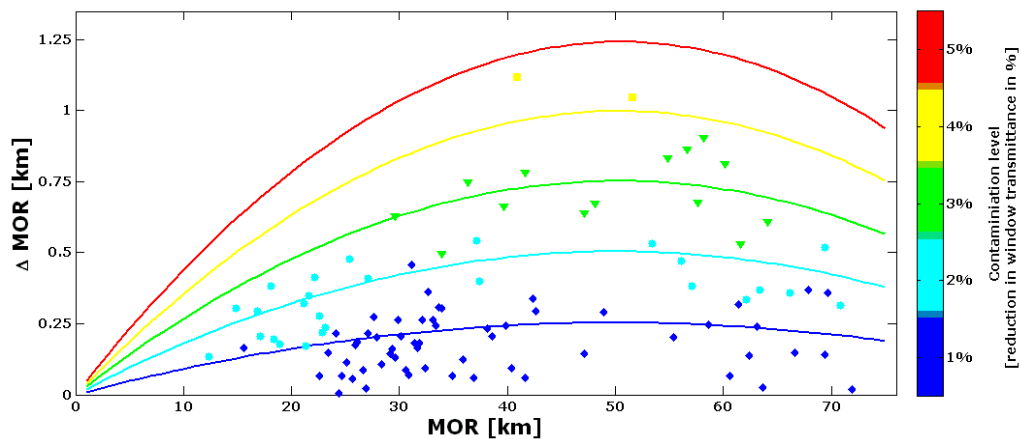
Fig. 3. Difference between MOR from clean and contaminated FS11 (diamonds) and soiling correction applied to the contaminated signal (lines). The colorbar shows the soiling level.

The FS11 scatter meters include a dirt compensation algorithm that corrects the systematic errors caused by dust deposition on the instrument's optics. The transmitter and the receiver are equipped with additional infrared LEDs and photodiodes that measure the reflectance of the sensor windows from the inside of the sensor housing. Thus contamination, damage or objects near the lens can be detected. The status of the windows is given as reduction in transmittance in 1% steps. The correction between raw MOR and output MOR is based on this value. The correction algorithm of the manufacturer was determined quantitatively by comparing the uncorrected and the corrected output signals of the FS11 time series for different soiling levels. The solid lines in Fig. 3 are displaying the contamination correction which is applied in the software. Through a series of tests the susceptibility to contamination of the FS11s was evaluated in further

experiments. Therefore, the deviation of two FS11 sensors (uncorrected MOR) was measured at different soiling levels and the difference was calculated. Two sensors were cleaned to provide one hour reference values. Afterwards the receiver and/or the transmitter of one of these sensors was/were soiled manually with fine dust and the second series was recorded. This procedure was repeated several times for different levels of contamination. Events during the complete time series where one FS11 sensor showed no contamination while the other FS11 sensor showed a certain contamination level have been considered as well. The results are shown in Fig. 3. The differences in MOR measurements between contaminated and clean sensors are small. The automatic soiling correction of FS11 matches the experimental results quite well. However, observations also showed that higher soiling levels result in a lower signal to noise ratio of the measurements.

Application in resource assessment and plant monitoring

For application in resource assessment and performance analysis in tower plants, the utilized sensors display different advantages and disadvantages. The FS11 is rather simple in installation. It can be mounted on windmasts or at different heights on a tower which simplifies the generation of exemplary extinction height profiles. The compact scatter sensors can even be used for resource assessment at remote sites due to its power and maintenance requirements. Several months of operation showed that FS11 scatter meters display a rather robust behavior concerning soiling or temperature- and wind changes. Uncertainty in τ for MORs lower than the detection maximum for FS11 is quite satisfying. The setup for both transmissometers, TR 30AC and LPV-4 demands high mechanical stability to deliver accurate measurements. The mounting of each sensor has to ensure robustness to wind or temperature changes. The shield windows of the LPV-4 have to be cleaned at least daily as the sensor is highly sensitive to soiling. One main advantage is that the LPV-4 is able to measure τ also on a non-horizontal path so that a mounting of the receiver directly on a tower is possible for performance analysis. For large working path distances, uncertainty in τ decreases quickly. Dirt compensation is implemented into the software of the TR 30AC, but regular cleaning should be performed every few days. Additionally, the TR 30AC requires higher power supply. Application for τ measurements with TR 30AC is rather practicable in environments with MORs lower than at PSA as the uncertainty restricts the reliable measurement range. These results limit the possibility of applying these transmissiometers for solar resource assessment at remote sites.

4.2. State of the art time series for PSA
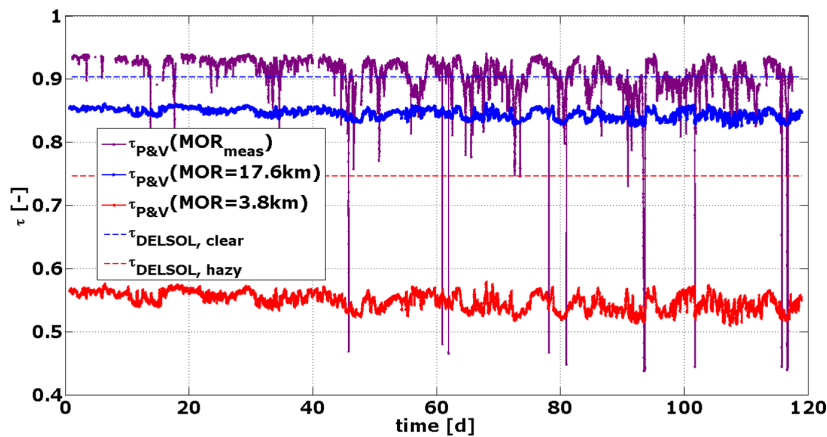
Fig. 4: Transmittance for an imaginary 200 m high tower at PSA, slant range of 1 km: Two <u>selected</u> MORs for DELSOL and P&V model and finally P&V model with measured MOR input.

Several months of MOR measurements were collected. Fig. 4 displays calculated transmittances with the P&V model as well as the DELSOL software. The purple curve in Fig. 4 shows the result of the P&V model including site and time resolved MOR input from PSA. MOR values have been derived using measurements of the FS11s. The MOR is the most relevant parameter for the variation of the transmittance. This can be seen by comparison to the solid red and blue curves that are calculated with the P&V model using constant MORs that are often suggested as standards and only varying water vapor input. Two standard cases from

DELSOL are also shown. Both, the deviations to the commonly used standard values and the variations of the modeled τ are high. This example shows that for PSA higher τ can be found than commonly used. One can conclude that site and time dependent input in such transmittance models increases the accuracy of tower performance calculations.

Fig. 5 displays an excerpt from Fig. 4 corresponding to a Sahara dust event at PSA on June 29, 2012 and the following days. DNI is also shown and a reduction can be seen during the first 2 days. This illustrates the expected coincidence of low DNI and high attenuation losses. However, the example also illustrates that the extinction coefficient in the boundary layer is not simply proportional to the optical depth of the complete atmospheric column. On June 30 the MOR was noticeably higher than on June 29 although no relevant change in DNI is found.
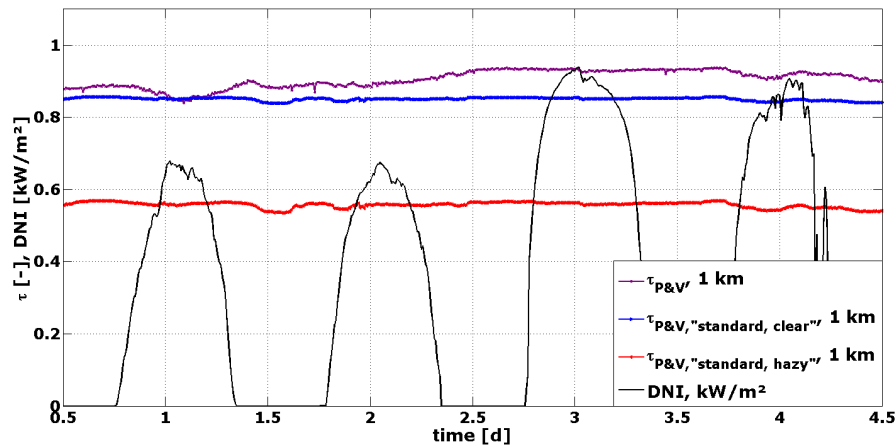

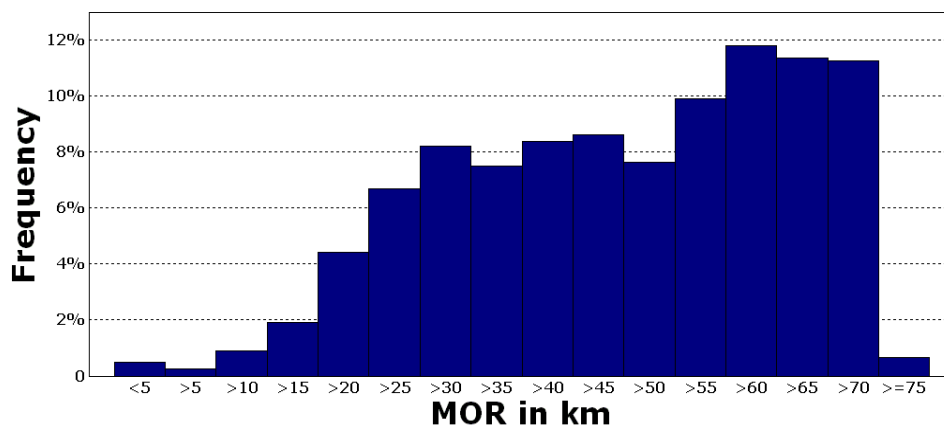**Fig. 5: Excerpt from Fig. 4 starting on June 29, 2012.**

Fig. 6: Histogram of MOR at PSA from May to August 2012 determined by one FS11.

The FS11 scatter meters show highest frequencies of occurrence of MORs between 55 and 70 km for PSA (Fig. 6). Both sensor types, the FS11 scatter meters and the TR 30AC transmissometer often measured high MORs up to the detection limit during the comparison campaign. These results can be affiliated to a clear mean atmosphere with low water vapor density and aerosol concentration at the PSA. Most applied models utilize extinction values corresponding to a MOR of about 17.6 km which displays for our measurements an overestimation of extinction. For other sites, e.g. Abu Dhabi airport, extinction might be underestimated (often "visibilities" of about 9-10 km [17]) and therefore the performance of tower plants is overestimated. Various airport sites such as Kuwait airport show strong varying "visibility" records of about 9 km to 30 km [18] (Hereby it is not clear if "visibility" corresponds to MOR or VR, but in both cases the mentioned underestimation of the extinction occurs when "standard" clear conditions are assumed).

Fig. 7 shows another measurement sample from PSA including also the aerosol concentration measurement. The resulting transmission for different slant ranges and a tower height of 200 m was calculated using the model from [1]. Some reductions of the MOR due to raised dust from a nearby construction site can be seen.

Also shown is the particle concentration measured with the collocated dust monitor Grimm EDM164. A correlation between the MOR and the particle concentration is found.
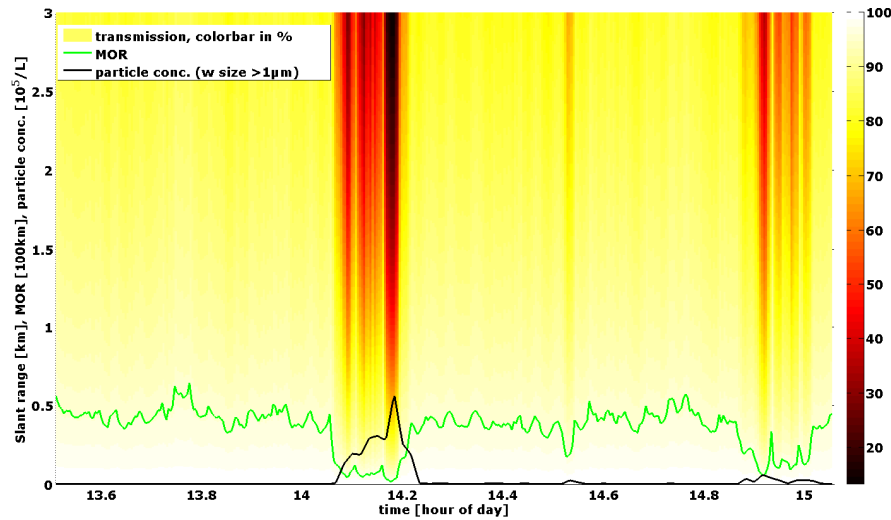
Fig. 7. Transmission calculated for measurements from the scatter meter FS11P at PSA. Also shown is the particle concentration measured with the collocated dust monitor Grimm EDM164.

5. Discussion of state of the art and recommendations

As already discussed in Section 2, the P&V transmittance model displays various limitations. It is only valid for distinct atmospheric conditions as it was designed based on specific vertical water vapor and aerosol density profiles. These are in many cases not displaying actual site characteristics.

Furthermore, scatter sensors and transmissometers can not be used in the physical model of P&V in the same way. The derived extinction coefficient β_e calculated in the model is defined as attenuation due to scattering by aerosols and air molecules and include absorption processes as well. As input parameter β_s is demanded, which only includes scatter processes. The extinction coefficient derived by scatter sensors is based only on scattering processes in the measurement volume. Transmissometers take both processes into account: scattering as well as absorption due to air including water vapor. Depending on the spectrum of the transmissiometer's lamp, water vapor can affect the measurement. Therefore, if β_e derived by measurements of a transmissometer is used for the P&V model, one has to be careful that attenuation due to water vapor is not taken twice into account as water vapor density also belongs to the input variables.

For most instruments spectral effects have to be corrected due to the use of band pass filters. Regarding these spectral aspects, one has to consider that the incoming spectrum of solar irradiance differs dependent on atmospheric conditions and also in the diurnal cycle [19]. As transmittance varies with wavelength, the spectrum used to perform the spectral integration in the model has to be chosen carefully. The chosen spectrum has to correspond to the conditions assumed for the attenuation calculations.

6. Conclusion and Outlook

Different sensors have been tested for the determination of atmospheric attenuation in solar tower plants. It was found that FS11 scatter meters can be used for solar resource assessment due to the fair maintenance requirements even at remote sites. Transmissometers can be used if intense maintenance is not an issue. Thus the necessary input for more accurate modeling of solar tower plants can be obtained. Several months of MOR measurements were presented.

The setup of different available instruments has been tested at the PSA to provide vertical profiles for aerosol concentration and particle size distribution in future: Three FS11 scatter meters will be mounted at different tower heights at PSA and the Optec LPV-4 transmissometer allows non-horizontal path measurements. Further measurements to deepen characterization of local atmospheric conditions will be performed. The dust

monitors including the additional instruments to measure temperature, relative humidity and ambient air pressure together with anemometers and wind direction sensors will be set up at the same heights where the FS11 will be mounted in order to create a database for parameterizations. Additionally these measurements facilitate a conclusion to the purpose of which spectral corrections of the sensor signals are necessary.

For more accurate modeling of central solar tower plants new height resolved measurements of the extinction coefficient should be provided. For that purpose and for quantifying height profiles of the extinction coefficient, a tiltable LIDAR system has been acquired. Wind, temperature and water vapor density profiles will complete the generation of extinction height profiles to determine atmospheric attenuation in solar tower plants.

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