ATMOSPHERIC ATTENUATION IN CENTRAL RECEIVER SYSTEMS FROM DNI MEASUREMENTS

Mananjit Sengupta  
National Renewable Energy Laboratory  
Golden, CO, USA

Michaël Wagner  
National Renewable Energy Laboratory  
Golden, CO, USA

ABSTRACT.

Atmospheric attenuation loss between the heliostat field and receiver has been recognized as a significant source of loss in Central Receiver System. Methods that can improve estimation of attenuation loss using available measurements will be useful in reducing uncertainty in estimation of CSP plant production, particularly in locations and climates that differ in atmospheric composition from typical arid desert locations. In clear sky situations, Direct Normal Irradiance (DNI) is primarily impacted by aerosols in the atmosphere. Aerosols extinct direct radiation with the photons either being absorbed or scattered based on the aerosols optical characteristics. As aerosol loading is high close to the surface, the attenuation loss between heliostat and receivers is significantly influenced by amount of aerosols present on a particular day. The purpose of the study is to understand the impact of aerosols on attenuation loss and model this loss as a function of ratio of measured DNI to a calculated DNI for an “aerosol-free” atmosphere. The assumption here is that the reduction in clear sky DNI due to aerosols when compared to a theoretical “clean environment” value can provide valuable information about aerosol loading at the surface and therefore attenuation loss between heliostat and receiver. Preliminary analysis shows that such an approach is viable.

Keywords: DNI, Attenuation Loss, Heliostat, Central Receiver, Aerosols

1. INTRODUCTION

Atmospheric attenuation loss between the heliostat field and receiver has long been recognized as a significant source of loss in Central Receiver Systems. Attenuation losses can potentially reach over 10% especially as distances between heliostats and receivers reach a kilometer or more. Historically this loss has been represented by parametric equations that are functions of distance between heliostat and receiver [1],[2],[3][4][5] with separate equations for different levels of aerosol loading. Individual equations do not directly account for variability in aerosols, which is the primary source of DNI losses close to the surface where most of the transmission between heliostat and receiver occurs. It is therefore possible that a model that directly accounts for aerosol variability close to the surface will lead to a better estimate of attenuation losses between heliostat and receiver. In this paper we build a model that directly accounts for aerosol variability with the expectation that it will provide a more accurate representation of the attenuation loss.

To get the most accurate estimate of attenuation between heliostat and receiver it is necessary to measure aerosol optical properties as well as water vapor mixing ratio profiles in the first few hundred meters from the surface where the heliostat and receiver lies. Such measurements are expensive and therefore generally not available. The other option is to obtain an estimate of aerosol optical depths close to the surface using available measurements. Making use of the fact that DNI measurements are generally available at central receiver system this study seeks to model attenuation loss close to the surface as a function of measured DNI. The theory and methodology behind this work is summarized in Section 2. Section 3 presents the results of the calculations and the model while Section 4 provides a brief summary and a description of future work.

2. METHODOLOGY

In clear sky situations, extinction of Direct Normal Irradiance (DNI) through either absorption or scattering is primarily from aerosols in the atmosphere. The ratio of absorption to scattering varies based on aerosol type. Accurate representation of that ratio is important for calculating diffuse radiation. On the other hand DNI loss estimation only requires knowledge of extinction and not the apportionment between scattering and absorption. The atmospheric constituents that impact solar radiation are the atmospheric gases and aerosols. Most atmospheric gases are well mixed and extinction of DNI resulting from those gases is easily calculated with minimal uncertainty. On the other hand the two most important variables that influence DNI which not well mixed are aerosols and water vapor. For our study it is advantageous that aerosol and water vapor loading primarily lies in the lower troposphere with much lower concentrations generally existing above the boundary layer. As aerosol loading is high close to the surface the attenuation loss between heliostat and receivers is significantly influenced by the magnitude and variability of aerosol amount. Based on this understanding of aerosol distribution we build a model that relates attenuation losses close to the surface to DNI measurements. This section is divided into three subsections. Section 2.1 outlines the theory used to develop a relationship between measured DNI and corresponding attenuation between heliostat and receiver in a central receiver system. Section 2.2 provides an outline of the radiative transfer model used in the calculations while Section 2.3 contains details about model inputs and the actual scenario used in this paper.

2.1 Theory

As previously mentioned we are concerned with DNI losses and do not require single scattering albedo (ratio of scattering to extinction) estimates. Therefore DNI at any height in the atmosphere can be represented as a function of the Top-of-Atmosphere DNI using the relationship.

\[ DNI = DNI_{TOA} e^{-\frac{\tau}{\cos(\theta)}} \]  

(1)

where, \( DNI_{TOA} \) is the Top-of-Atmosphere DNI, \( \tau \) is the extinction optical depth of the atmospheric column and \( \theta \) is the solar zenith angle. We can then use Equation 1 to defining aerosol forcing \( F \) as

\[ F = \frac{DNI_{a}}{DNI} = e^{-\frac{(\tau_a-\tau)}{\cos(\theta)}} \]  

(2)
where DNI\textsubscript{s} represent the measured DNI in an atmosphere that contains aerosols while DNI\textsubscript{b} represents a baseline theoretically calculated clean atmosphere with no aerosols for the same sun position and therefore the same zenith angle and earth to sun distance. Using Equation 2 the difference in optical depth between DNI\textsubscript{s} (an atmosphere with aerosols) and DNI\textsubscript{b} (a “clean” baseline atmosphere with no aerosols) can be represented as

\[ X = (\tau_a - \tau_b) = -\log(F) \times \cos(\theta) \]  

(3)

Using a relationship similar to Equation 1 we can represent the DNI at the surface as a function of the DNI received at a layer \( \Delta z \) above the surface. This relationship is

\[ DNI_{sfc} = DNI_i \times e^{-\tau_{s_i}} \]  

(4)

where, \( DNI_i \) and \( DNI_{sfc} \) represent the DNI at the surface and a level \( \Delta z \) above the surface and \( \tau_{s_i} \) represents the optical depth of the surface layer. Equation 4 can then be used to represent the optical depth of an atmospheric layer \( \Lambda z \) that lies between the surface and any height \( z \). The relationship is

\[ Y = \tau_{s_{\Delta z}} = -\log\left(\frac{DNI_{sfc}}{DNI_i}\right) \times \cos(\theta) \]  

(5)

2.2 Radiative Transfer Model

The radiative transfer model that we used in this study is based on the 62 stream numerical algorithm presented by [6] and [7], which bears the acronym RAPRAD (Rapid Radiative Transfer) to signify its speed of computation. The model has 32 spectral intervals ranging from 0.24 \( \mu m \) to 4.6 \( \mu m \) in the shortwave and near-infrared, using absorption coefficients based on \( k \) distributions and a correlated-\( k \) approximation as explained in detail by [8].

The top of atmosphere spectral solar irradiance in the RAPRAD model is based on the solar irradiance of MODTRAN3 (MODerate resolution atmospheric TRANsmission) [9] using the Kurucz database [10]. The RAPRAD model incorporates ozone, oxygen, carbon dioxide and water vapor absorption, as well as water vapor continuum absorption. The molecular scattering optical depth is calculated using the Rayleigh optical depth calculation as shown in [11].

For RAPRAD model inputs based on high-quality measurements at the United States Department of Energy’s Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) Cloud and Radiation Testbed (CART) site measurements, calculated surface fluxes are generally within 15-20 W/m\textsuperscript{2} of surface flux measurements [12].

2.3 Simulation Design

The atmospheric layers in the RAPRAD model are arbitrary and can be set according to the requirements of the problem at hand. We set the top of atmosphere at 70 km and divided the atmosphere below 16 km into 250 m thick layers. Above 16 km model layer thicknesses are set to increase with altitude. In the model simulations we use a surface albedo of 0.2 that is invariant with wavelength; this value is typical of the surface albedo of farmland in the mid-visible (e.g. Blythe, CA Typical Meteorological Year surface albedo from http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/). Clear-sky RAPRAD irradiance calculations require vertical profiles of pressure, temperature, water vapor, ozone, and aerosol particles. We used a mid-latitude summer atmospheric profile from MODTRAN [9] for pressure, temperature, water vapor mixing ratio and ozone profiles. Our baseline clean case contains no aerosols. For externally mixed aerosol we use mineral dust with the Angstrom exponent value [13] from [12]. The aerosol is taken to be evenly distributed in the lowest 1000 m of the atmospheric column. DNI is calculated for 0.5 degree increments with the zenith angle varying from 0-80 degrees.

3. RESULTS

RAPRAD was run at 1-minute increments during the period of a day. For determining solar position during the time of the day we considered July 21 at Golden, CO. Calculations were done as previously mentioned for a mid-latitude summer atmospheric profile for a station assumed to be at sea level. The calculations were run for a baseline case with no aerosols as well as for various increasing levels of aerosol optical depths (AOD) ranging from 0.0125 to 0.1. RAPRAD produces DNI and Global Horizontal Irradiance (GHI) at the boundaries of every atmospheric model layer for each of the 32 spectral intervals. The broadband DNI is calculated by summing the spectral DNI. Figure 1 shows how the DNI varies during the day with each line representing various aerosol optical depths. It is seen that DNI can be reduced by around 200 W/m\textsuperscript{2} for a change in AOD of 0.1. As all other atmospheric properties were held constant it is obvious that the reduction in DNI is a result of increase in AOD.

While Figure 1 shows how the DNI changes for various AOD’s Figure 2 shows the attenuation in DNI in the lowest 250 m of the atmosphere where a power tower will operate. Effectively Figure 2 shows the difference in DNI at a level 250 m above the surface (not shown) and the surface (Figure 1). We can see that AOD difference of less that 0.1 can result in losses of around 40 W/m\textsuperscript{2}.

As mentioned above the goal of this work is to relate the attenuation of DNI reflected towards the receiver in the layer closest to the surface to measured DNI in the presence of aerosols. To establish this relationship we relate X (the difference between
the optical depth used to calculate a baseline DNI and the optical
depth of the atmosphere for a measured DNI) and \( Y \) (optical
depth of the layer closest to the surface) in Equation 3 and Equation 5
respectively.

Figure 3 shows the relationship between \( X \) (the total optical depth
difference calculated in Equation 3) and the \( Y \) (optical depth of the
lowest 250 m atmospheric layer). The colored lines show that the
relationship is fairly constant for the whole range of zenith angles if
the AOD is constant. The black line is a least square fit to the
means calculated for each of the various colored datasets each
representing fixed AOD but varying solar zenith angles. It is
obvious from Figure 3 that the relationship with the means is
robust. This is borne out of the fact that the coefficient of
determination (Table 1) which is an indicator of the variance that is
explained by the model is nearly 100%. Figure 3 shows that there is
a zenith angle dependence on the relationship between \( X \) and \( Y \).
This primarily arises from some wavelength bands becoming
saturated as the airmass increases with zenith angle.

\[
DNI_{\text{rec}} = DNI_{\text{sf}} e^{-\frac{Y d}{250}}
\]  

(7)

The relationship in equation 7 is dependent on the accuracy of DNI
measurement at the heliostat. Typically, for well maintained sites,
DNI accuracy is +/- 2.0%, or +/-20 W out of 1000 W full scale (for
very well maintained measurements). It should be noted that \( DNI_{\text{sf}} \)
in Equation 4 is the actual DNI reaching the surface while the
\( DNI_{\text{sf}} \) in Equation 7 is the DNI that is reflected from the heliostats
and factors in cosine losses, shading losses, blocking losses and reflectivity.

3. VISIBILITY BASED ATTENUATION MODEL

In the absence of DNI measurement we can still estimate
attenuation between heliostat and receiver if we had a measurement
of visibility. As mentioned previously empirical models (e.g.
[1][2][3][4][5]) have been developed over the years establishing the
relationship between heliostat and receiver distance as a function of
visibility. A recent comparison by Ballestrin and Marzo [14]
showed that the model in [4] performed better than the model in
[1]. They also showed that the empirical models still have
significant errors when compared to theoretical calculation using
the [9] radiation transfer model. In this paper we analyze the
differences between the empirical models in [1] and the
calculations in [14] and find the differences explainable. We then
provide a simply parametric model that can estimate attenuation
between heliostat and receivers when a visibility measurement is
available.

3.1 COMPARISON OF PARAMETRIC MODELS

Ballestrin and Marzo [14] used MODTRAN to compute
atmospheric attenuation at sea level for visibilities of 5 km (hazy)
and 23 km (clear) using rural atmospheric conditions for a clear
day. Atmospheric attenuation for various slant ranges were
computed for those two cases and then compared to the attenuation
computed from Vititoe and Biggs’ [1] DELSOL model. The
comparison showed significant differences in the attenuation
arrived at from the two models and are reproduced in Table 2.

Table 1: The linear least squares fit shows that a robust relationship
exists between the column optical depth difference when
comparing the measured value to a clean atmosphere DNI and the
optical depth of the lowest atmospheric layer (in this case 250 m).

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1 (slope of regression fit)</td>
<td>0.2299 (95% confidence bounds [0.2269, 0.2329])</td>
</tr>
<tr>
<td>P2 (intercept of regression fit)</td>
<td>0.002674 (95% confidence bounds [0.002223, 0.003126])</td>
</tr>
<tr>
<td>Sum of squares of residuals</td>
<td>6.0907e-7</td>
</tr>
<tr>
<td>Coefficient of Determination R²</td>
<td>0.9998</td>
</tr>
</tbody>
</table>

Using the relationship represented by the black line in Figure 3 we
can determine the attenuation between heliostat and receiver if the
distance between the two is known. The relationship in the case is
represented by

\[
Y = 0.2299 \times X + 0.002674
\]

(6)

where \( Y \) is the optical depth of the bottom 250 m atmospheric
layer. The intercept in Equation 6 represents attenuation in the 250
m atmospheric layer in the absence of aerosols. Therefore if the
distance \( d \) between heliostat and receiver is known the DNI at the
receiver is

Figure 2: Attenuation of DNI in the lowest 250 m of the
atmosphere for various aerosol optical depths. Note the
low level of attenuation in the absence of aerosols as
shown by the green solid line.

Figure 3: This figure shows how the optical depth of
the lowest 250 m of the atmosphere is related to the difference
in total optical depth between a clean atmosphere and an
atmosphere with an aerosol optical depth represented in
the legend. The black line represents the least square fit to
the mean optical depth for each fixed AOD case
Ballestrin and Marzo [14] state that the Vititoe and Biggs [1] expressions are slightly dependent on altitude even though they were derived from observations taken at a specific site. This site was located in Barstow CA which is at an elevation of over 650 m. As aerosols are primarily distributed in the boundary layer, significant variation in aerosol concentrations occur based on site elevation. We therefore investigated whether the differences shown in Table 2 are related to the elevation difference resulting from the Ballestrin and Marzo [14] computations being done at sea level.

### 3.1.1 Explaining Differences in Empirical Models

Attenuation (A) of beam radiation is primarily influenced by the aerosol optical depth (AOD) between heliostat and receiver. The relationship can be expressed as

\[ A = 1 - \exp(-AOD) \]  

(8)

We can therefore translate the attenuation for various path lengths in Ballestrin and Marzo [14] to AOD’s as shown in Table 3 for 5 km visibility. The attenuation from Ballestrin and Marzo [14] is used in Equation 8 to calculate the AOD for the various distances between heliostat and receiver (Table 3). Using the AOD for the various slant lengths the AOD for the visibility distance (23 km) is calculated as an average. This value is shown at the bottom of Table 3.

Visibility can be defined as the distance where the beam radiation is close to being fully attenuated. As attenuation of solar radiation is a negative exponential function related to AOD as shown in equation 1 an AOD of approximately 3 results in over 96% of the radiation being attenuated. As attenuation increases slowly beyond an AOD value of 3 we assume that the threshold of visibility is reached at an AOD value of 3. The AOD’s for the visibility length shown at the bottom of Table 3 and in Table 4 are indeed seen to have values around 3 and shows that we can relate visibility to a standard AOD value.

### 3.1.2 Estimating Visibility from Scale Height

The scale height method of Gueymard and Thevenard [15] provides a convenient way to compute aerosol optical depth (AOD) for various elevations under the assumption that AOD at higher elevations (h) is lower than at sea level. The relationship used is

\[ \text{AOD}(h) = \text{AOD}(0) \exp(-h/\text{Ha}) \]  

(9)

where Ha is the scale height. Gueymard and Thevenard [15] suggest that a scale height of 2900 m for inland sites.

Using the AOD corresponding to visibility from Table 3 we can calculate the AOD at various elevations using equation 9. The AOD calculated for various elevations can then be converted to an equivalent visibility by calculating the distance at various elevations that would have the same AOD as the equivalent sea level AOD corresponding to visibility. Table 3 shows such a scale height conversion and a calculation of equivalent visibility for 23 km visibility at sea level.

It is obvious from Table 4 that the equivalent visibility at Barstow (elevation ~0.7 km) is approximately 29 km for a 23 km visibility at sea level. Assuming that aerosols are evenly distributed we can calculate the AOD’s at various slant lengths at Barstow for a visibility of 29 km (equivalent sea-level visibility 23 km). The AOD’s for the various slant lengths in Table 1 are around 80% of the AOD’s at sea-level. This reduction in AOD for the various slant lengths will result in differences in attenuation.

For 23 km visibility the difference between MODTRAN calculations and DELSOL from Ballestrin and Marzo [14] are shown in Table 2 and also Table 5 (column 4). From Table 5 we can see that the attenuation differences from Ballestrin and Marzo [14] shown in column 4 are within the ranges shown in columns 5-9. As columns 5-9 of Table 5 represent the reduction in AOD for the various slant lengths for an elevation of 0.7 km we can reasonably state that the DELSOL model is appropriate for that elevation but not applicable to other elevations without necessary corrections.

### 4. CALCULATING ATTENUATION FROM VISIBILITY

As previously mentioned an AOD of around 3 will result in beam attenuation of over 96%. Therefore, assuming that visibility is defined as the distance leading to an attenuation of around 96% we can easily calculate attenuation if visibility is known. The simple relationship between visibility, V and attenuation A for a slant length, d can be expressed as

\[ A = 1 - \exp(-3*d/V) \]  

(7)
A variety of atmospheric profiles and aerosol distributions. Additionally surface elevation needs to be accounted for to make the model applicable at all locations. As a change in surface pressure due to elevation has a linear impact on the optical depth for well-mixed gases this scaling factor will be added to the baseline DNI to make the model applicable at all elevations. Finally as previously mentioned there is a small zenith angle dependence between DNI and attenuation close to the surface. This will also be considered in our future work.

This simple relationship can then calculate attenuation between heliostat and receiver \((d)\) if visibility \((V)\) is known. This model can then be used to calculate attenuation between heliostat and receiver in the absence of a DNI measurement. Figure 2 shows how attenuation is related to the distance between heliostat and receiver and visibility.

<table>
<thead>
<tr>
<th>Elevation (km)</th>
<th>AOD</th>
<th>Visibility (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>3.43</td>
<td>23</td>
</tr>
<tr>
<td>0.1</td>
<td>3.32</td>
<td>24</td>
</tr>
<tr>
<td>0.2</td>
<td>3.20</td>
<td>25</td>
</tr>
<tr>
<td>0.3</td>
<td>3.09</td>
<td>26</td>
</tr>
<tr>
<td>0.4</td>
<td>2.99</td>
<td>26</td>
</tr>
<tr>
<td>0.5</td>
<td>2.89</td>
<td>27</td>
</tr>
<tr>
<td>0.6</td>
<td>2.79</td>
<td>28</td>
</tr>
<tr>
<td>0.7</td>
<td>2.70</td>
<td>29</td>
</tr>
<tr>
<td>0.8</td>
<td>2.60</td>
<td>30</td>
</tr>
<tr>
<td>0.9</td>
<td>2.52</td>
<td>31</td>
</tr>
<tr>
<td>1</td>
<td>2.43</td>
<td>32</td>
</tr>
</tbody>
</table>

Table 4: Equivalent visibility for various elevations corresponding to a surface visibility of 23 km.

This simple relationship can then calculate attenuation between heliostat and receiver \((d)\) if visibility \((V)\) is known. This model can then be used to calculate attenuation between heliostat and receiver in the absence of a DNI measurement. Figure 2 shows how attenuation is related to the distance between heliostat and receiver and visibility.

<table>
<thead>
<tr>
<th>Slant length (m)</th>
<th>Attenuation (Ballestrin and Marzo)</th>
<th>AOD</th>
<th>Difference (MODTRAN – DELSOL)%</th>
<th>Attenuation Differences (%) for various AOD ratios</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>2.5</td>
<td>0.025</td>
<td>0.3</td>
<td>0.85  0.8  0.75  0.7  0.65</td>
</tr>
<tr>
<td>500</td>
<td>7.5</td>
<td>0.078</td>
<td>2.0</td>
<td>0.4   0.5   0.6   0.7   0.9</td>
</tr>
<tr>
<td>1000</td>
<td>13.8</td>
<td>0.149</td>
<td>4.1</td>
<td>1.1   1.5   1.8   2.2   2.6</td>
</tr>
<tr>
<td>2000</td>
<td>24.5</td>
<td>0.281</td>
<td>7.5</td>
<td>1.9   2.6   3.3   3.9   4.6</td>
</tr>
<tr>
<td>4000</td>
<td>41.1</td>
<td>0.529</td>
<td>7.6</td>
<td>3.3   4.4   5.5   6.6   7.8</td>
</tr>
</tbody>
</table>

Table 5: Differences in Attenuation for various slant heights resulting from a reduction in AOD for the 23 km visibility case. Note that the range of differences in attenuation for the various slant lengths matches the differences between MODTRAN and DELSOL calculation shown in column 4.

5. CONCLUSION

Equation 7 provides a model for attenuation losses between heliostat and receiver in a central receiver system that depends only on DNI measurements. As DNI measurements are generally available at any prospective CSP site or existing CSP plant such a model can be readily used in CSP production modeling. The model can be incorporated in available models such as the National Renewable Energy Laboratory’s Solar Advisor Model (SAM).

This model relies on the fact that atmospheric constituents that are not well mixed but significantly influence DNI are primarily present close to the surface. This is especially the case of aerosols as they are primarily present below the atmospheric boundary layer. We have not investigated how sensitive the relationship we have derived is to other atmospheric profiles such as those present in the tropics. It is expected that the intercept in Equation 6 will vary to accommodate various levels of precipitable water vapor at the surface. We also have considered the case where the aerosols are uniformly distributed in the lowest 1000 m of the atmosphere. In future work our goal is to carry out the same modeling on a variety of atmospheric profiles and aerosol distributions.

Visibility measurements have been available for a long time perhaps because of the availability of trained human observers. Significant effort has been made since the 1970’s to relate attenuation to the distance between heliostat and receiver for various situations of visibility. Vittitoe and Biggs [1] developed a parametric fit equation for low and high visibility cases. Recently Ballestrin and Marzo[14] showed that Vittitoe and Biggs’ DELSOL model provides significantly different results from MODTRAN calculations of attenuation. We find that the DELSOL model is consistent with the datasets it was derived from and the differences arise mainly from the elevations at which the calculations in the two models were made. The MODTRAN simulations were done at sea-level while the DELSOL model was derived using datasets from Barstow, CA located at around an elevation of 700 m. We also create a simple model that relates attenuation between heliostat and receiver in the absence of DNI measurements. This model defines visibility distance as a path length with an optical depth of 3. An optical depth of 3 in effect attenuates 96% of a beam and is therefore treated as the limiting optical depth for visibility. Using this assumption we derived a simple relationship that can estimate attenuation between heliostat and receiver given the
distance between the two and visibility. The relationship appears to be consistent with the theoretical calculations of Ballestrin and Marzo [14].

ACKNOWLEDGEMENTS AND DISCLAIMER

The Alliance for Sustainable Energy, LLC (Alliance), is the manager and operator of the National Renewable Energy Laboratory (NREL). Employees of the Alliance, under Contract No. DE-AC36-08GO28308 with the U.S. Dept. of Energy, have authored this work. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

6. REFERENCES