Analysis of atmospheric influences on ratio thermography for solar tower systems

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Abstract

The knowledge of temperature and emissivity of the receiver are both critical for a solar tower power plant, in order to guarantee an efficient operation of the thermal receiver on the one hand, while monitoring any degradation of the receiver coating on the other hand. To make these measurements, a new thermographic system is currently being developed, using a multispectral camera working in the short wavelength infrared spectrum. This system applies the principle of ratio thermography, using a couple of narrow bandpass filters centered on atmospheric water absorption bands, at 1.4 and 1.9 µm, to reduce the influence of solar reflections on the measurement signal, making it sensitive to atmospheric conditions.

In this thesis, a batch simulation approach is used to identify boundary atmospheric and operating conditions necessary to achieve temperature errors below 2 %, minimizing the influence of solar reflection. Furthermore the influence of atmospheric parameters on the sensitivity of ratio thermography is analyzed, in particular the validity of the gray body assumption. It is shown that the atmosphere has a critical influence on the measurement accuracy. A humid atmosphere and/or high zenith angle is necessary for making accurate measurements. Furthermore only receiver temperatures above 450°C could be measured for the current system configuration, regardless of atmospheric conditions. Assuming negligible solar reflections, the validity of the gray body assumption is shown to be sensitive to the precipitable water vapor. A model based atmospheric compensation is therefore required to further improve the accuracy of ratio thermography.

Keywords:
Concentrated solar power, Ratio thermography, Shortwave infrared, gray body assumption, Atmospheric compensation

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Nomenclature

Physics Constants

\begin{align*}
c & \quad \text{Speed of light in a vacuum} \quad 299\,792\,458 \text{ m s}^{-1} \\
h & \quad \text{Planck constant} \quad 6.62607015 \times 10^{-34} \text{ J Hz}^{-1} \\
\sigma & \quad \text{Stefan-Boltzmann constant} \quad 5.670374419 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4} \\
b & \quad \text{Wien’s displacement constant} \quad 2.897771955 \times 10^{-3} \text{ m K} \\
K_b & \quad \text{Boltzmann constant} \quad 1.380649 \times 10^{-23} \text{ J K}^{-1}
\end{align*}

Abbreviations

\begin{align*}
AM & \quad \text{Air mass} \\
AOD & \quad \text{Aerosol optical depth} \\
CSP & \quad \text{Concentrated Solar Power} \\
CWL & \quad \text{Central wavelength} \\
DNIR & \quad \text{Direct normal irradiance} \\
FIR & \quad \text{Far infrared} \\
HW & \quad \text{Half width} \\
IR & \quad \text{Infrared} \\
LWIR & \quad \text{Long-wave infrared} \\
MWIR & \quad \text{Mid-wave infrared} \\
OD & \quad \text{Optical depth}
\end{align*}
$PV$  Photovoltaics

$PWV$  Precipitable water vapor

$RMSE$  Root mean square error

$SMARTS$  Simple Model of the Atmospheric Radiative Transfer of Sunshine

$SWIR$  Short-wave infrared

$UV$  Ultraviolet

**Other Symbols**

$\alpha$  Absorptance

$\lambda$  Wavelength

$\phi$  Azimuth angle

$\rho$  Reflectance

$\tau$  Transmittance

$\theta$  Zenith angle

$\varepsilon$  Emittance

$\varphi$  Elevation angle

$AM0$  Extraterrestrial spectrum

$C_x$  Concentration factor

$CR$  Camera spectral response

$H_w$  Scale height

$T$  Temperature
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Chapter 1

Introduction

1.1 World Energy Overview

As the world’s electricity demand continues to reach new highs, as illustrated in figure 1.1, and the global land and ocean surface temperature is estimated to have increased by 1.1°C from the 1850-1900 yearly average [1], one can argue that the importance of sustainable energy sources is now greater than ever. Once the global average temperature is increased by 1.5-2°C, the intensity and frequency of extreme events such as storms, heat waves, floods etc. will increase. Therefore a global average temperature increase will have a noticeable impact on society. To prevent global warming, substituting non-renewable energy sources with renewable energy sources greatly reduces the CO₂ output, which is vital in order to reach the goal of a fully decarbonized power sector by 2050 [11].

As seen in figure 1.2, oil, natural gas and coal contributed to 63.1% of the global energy mix in 2019, while renewable energy sources and waste was estimated to contribute to 26.5% [12]. This shows that there is still a great need for expanding the renewable energy market.

Solar power technologies are estimated to contribute to only 2.6% of the global energy mix [12]. With their low impact on the environment, there is good reason for improving the technology and reducing its costs, to make it a more viable option when expanding the renewable energies. There are two types of solar power technologies, Concentrated Solar Power (CSP) and Photovoltaics (PV). As of now about 98% of the implemented solar power consist of PV and 2% is CSP [13].
Figure 1.1: Global changes in electricity demand 2015-2022 [TWh/year], drop 2020 due to covid [1]

Figure 1.2: Global electricity mix 2019 [1]
1.2 Concentrated Solar Power (CSP)

CSP technologies are based on the concept of using mirrors to focus beams of sunlight onto a receiver. As the receiver is heated up by the concentrated solar radiation, it will in turn transfer the heat to a fluid that is transported to a turbine which generates electricity. Heat storage systems can also be integrated to store thermal energy, which can later be used to generate more electricity. This is an advantage compared to PV systems, where it is not possible to store any thermal energy, but instead the energy has to be stored as electricity in electrochemical batteries. The thermal storage method is deemed to be 80-90% more cost effective than battery storage [13]. Being able to store energy with a high efficiency is important since it can be saved for times with high electricity demand.

According to IEA’s report on CSP technology [2], CSP is not on track with the Net Zero Emissions by 2050 scenario. As illustrated in figure 1.3, the goal for CSP is to generate 200 TWh by 2030 to be in line with the Net Zero Emissions scenario. In 2020 CSP generated a total of 14.5 TWh, a five percent increase from 2019. To reach the Net Zero Emission goal, CSP technology needs an annual growth of 31% until 2030, although these goals are known to be optimistic. A more realistic expectation could be to assume that the linear growth seen during the past 10 years continues. As seen in IRENA’s report about power generation costs, the total installed costs for CSP plants fell by 50% from 2010 to 2020 [14]. It is plausible that the cost for CSP will continue to decrease as storage capabilities increase and the technology becomes more efficient, hence it would be reasonable to assume that the CSP technology will see continued growth.

A lot of variables have to be taken into consideration when comparing the costs between PV and CSP, but it can be shown that CSP systems are able to compete with PV in terms of cost [13]. Since PV systems do not generate a continuous supply of electricity, CSP technologies can act as a complementary system being able to continuously generate electricity in a more efficient way due to heat storage, making it possible to have a stable power grid using only solar energy. As seen in figure 1.4, the market for PV systems is far more established than the market for CSP, giving PV systems the benefit of cost reduction due to mass production. As the market for CSP is small at the moment, it has yet to benefit from the cost reduction of mass production.

Since there is value in having hybridized systems, CSP do not have to necessarily compete with PV systems [15].
Figure 1.3: CSP generation in Net Zero Scenario [TWh/year] [2]

Figure 1.4: Installed capacity for PV and CSP systems [MW/year] [3]
1.2. Concentrated Solar Power (CSP)

CSP is heavily reliant on having high direct normal irradiance (DNIR), which is why most of the CSP power plants can be found in subtropical regions. There are currently 23 countries in the world which use or construct CSP power plants, and the distribution of CSP generated electricity per country can be seen in figure 1.5.

![Figure 1.5: Installed CSP per country [4]](image)

The four basic variants used for concentrating the solar radiation can be divided into two categories, point focusing and line focusing. The point focusing technologies focus the solar radiation onto a point like object, whereas the line focusing systems focus the solar radiation onto a line. These categories have two variants each. The variants of the point focusing technologies are solar towers and parabolic dish systems. The variants of line focusing technologies are parabolic trough and linear fresnel systems.

- **Solar Tower:** A solar tower plant uses two axis tracking mirrors, called heliostats, to reflect the solar radiation onto a central receiver located on the top of a tower. As the heliostats concentrate the solar radiation onto the receiver, it normally heats up to 300-700°C, and it will then heat the transfer fluid that will be used for storing the energy or directly used for driving a turbine to generate electricity. The heat transfer fluid normally used in solar tower plants are molten salts, steam or air.
• **Parabolic dish:** A parabolic dish system also uses a parabolic mirror, but as the name suggests it is shaped as a dish instead of a trough. The parabolic dish system does not use a transfer fluid to store thermal energy, a stirling engine is installed directly onto the dish making it possible to heat the receiver to up to 1500°C. This extremely high temperature makes the parabolic dish systems good candidates for making solar fuels, but since no thermal energy is stored, it is less suitable for generating electricity.
• **Parabolic trough:** Parabolic trough power plants use parabolically shaped mirrors to focus the solar radiation on an absorber tube mounted along the focal line. The concentrated solar radiation heats the tube, which in turn heats a thermal oil that is pumped through it. The parabolic trough systems are the most common type of commercially implemented CSP.

![Figure 1.8: Parabolic trough [5]](image)

• **Linear fresnel:** Linear fresnel systems are similar to parabolic trough systems, but instead of using parabolically shaped mirrors, they use flat mirrors to concentrate the solar radiation on to the absorber tube located above the mirrors. Since the mirrors are flat they have a lower wind load compared to the parabolic trough, and are suitable to mount on flat roof tops. However they have a lower efficiency than the parabolic trough, and are therefore used less in commercial power plants.

![Figure 1.9: Linear fresnel system [5]](image)
1.3 Motivation

The knowledge of temperature and emissivity of the receiver are both critical for a solar tower power plant, in order to guarantee an efficient operation of the thermal receiver on the one hand, while monitoring any degradation of the receiver coating on the other hand. It is therefore of interest to have good equipment for keeping track of these.

Current CSP systems often use an infrared (IR) camera working in the long wavelength infrared spectrum to measure the temperature and emissivity. A new thermographic system is currently being developed, using an IR camera working in the short wavelength infrared spectrum instead. This is also designed to measure the temperature and emissivity, but is expected to require less a priori knowledge of the emissivity of the receiver and atmospheric transmittance.

The camera uses the water absorption bands of the atmosphere to measure the infrared radiation of the receiver in spectral bands where most of the solar radiation is absorbed by the atmosphere. This maximizes the signal to noise ratio (SNR), since there is less interference from the surroundings. However this makes the calibration of the camera sensitive to the water vapor in the atmosphere, how much atmosphere the radiation passes through, the aerosol depth and more. It is therefore of interest to investigate how sensitive the new system is to these parameters. In this thesis, the effect of the atmospheric influence on the measurement is investigated and the conditions required for accurate measurements are mapped out.

First a primer regarding basic theory of radiation, optics and atmosphere is given. Then the measurement technique of infrared thermography is explained for the application of a solar tower. With this knowledge, the methodology used for deriving the results is explained. Then the results are interpreted and this is followed by a conclusion.
Chapter 2

State of the art

2.1 Theory

2.1.1 Electromagnetic radiation

Electromagnetic radiation is the propagation of electromagnetic waves through space. The wavelength of these waves are related to the radiant energy they carry, as described by the Planck-Einstein equation 2.1. The equation describes the energy of a quantum of the electromagnetic field, known as a photon.

\[ E = \frac{hc}{\lambda} \]  

(2.1)

Since the energy of the wave has an inverse relationship to the wavelength, waves with shorter wavelength carry more energy. Because the energy of the electromagnetic radiation is directly correlated to its wavelength, it is often represented by an electromagnetic spectrum. In the electromagnetic spectrum, the wavelengths are classified into gamma rays, X-rays, ultraviolet, visible, infrared, microwave and radio, starting from the shortest wavelength. This is shown in figure 2.1.

In this study, the IR radiation is of interest since that is the range where blackbodies radiate energy as a function of their temperature under most conditions, as described in 2.1.3. This is also the reason why the camera works in the IR range. The IR radiation is commonly classified as the electromagnetic radiation with a wavelength \( \lambda \in \{0.8\mu m, 1mm\} \). However, this range is also divided into sub-ranges, due to the different applications. The exact definitions of the sub-ranges may vary, but a commonly used classification is:

Englin, 2022.
• short-wave infrared (SWIR) $\lambda \in [0.8\mu m, 1.7\mu m]$
• mid-wave infrared (MWIR) $\lambda \in [1.7\mu m, 5\mu m]$
• long-wave infrared (LWIR) $\lambda \in [8\mu m, 14\mu m]$
• far infrared (FIR) $\lambda \in [14\mu m, 1mm]$

This sub-range scheme is shown in figure 2.1. While most IR cameras work in the LWIR range, the camera currently being developed and used in this study works in the intersection of the SWIR and MWIR ranges.

![Figure 2.1: The electromagnetic spectrum zoomed in on the IR spectrum [6]](image)

The gap between the MWIR and LWIR range is due to an absorption band in the atmosphere, making it impossible to perform IR measurements in that range.

2.1.2 Optics

When electromagnetic radiation passes through a medium, its characteristics changes depending on the properties of the medium. While travelling in a homogeneous medium, the electromagnetic waves always travel in a straight line. Whereas when the medium changes, the radiation can change direction as it gets transmitted, but it can also be reflected or absorbed.
When radiation with an energy \( E \) is transmitted through a medium with a transmittance \( \tau \), it gets attenuated and the amount that passes through the medium is \( E\tau \). It can also be reflected from the surface of the medium, with a reflectance \( \rho \), such that \( E\rho \) is scattered off the surface of the medium.

If the waves are neither transmitted nor reflected from the medium, they will be absorbed by it with an absorption coefficient \( \alpha \), thus holds the following equation 2.2

\[
1 = \rho + \alpha + \tau \tag{2.2}
\]

### 2.1.3 Black body radiation

Every body with a temperature \( T > 0 \, \text{K} \) radiate thermal energy in form of electromagnetic waves. The physical laws that govern how the energy is radiated can be described by a set of equations that will be described in this chapter.

The spectral density of radiation emitted by an object follows Planck’s radiation law 2.3. As the temperature of the object increases, so does the amount of emitted radiation.

\[
E(T, \lambda) = \frac{2\pi hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda KBT}} - 1} \quad [\text{Wm}^{-3}],
\]

where the unit should be interpreted as watt per square meter per wavelength, and not watt per cubic meter. For short wavelengths, where \( hc \gg \lambda K_B T \), Wien’s approximation can be made, simplifying Planck’s law to 2.4.

\[
E(T, \lambda) \approx \frac{2\pi hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda KT}}} \quad [\text{Wm}^{-3}]
\]

The emitted radiation is also dependent on the wavelength, and as can be seen in figure 2.2, the wavelength in which the most radiation is emitted changes depending on the temperature of the object.
The relationship between the peak wavelength and temperature is obtained by taking the derivative of Planck’s law with respect to the wavelength, and finding where this equals zero. The result is called Wien’s displacement law 2.5.

\[ \lambda_{\text{peak}} = \frac{b}{T}, \]  

where \( b = 2.898 \, \mu mK \) is Wien’s displacement constant.

The total amount of radiation emitted by an object is calculated by integrating Planck’s law over the wavelengths.

\[ P = E(T) = \int_0^\infty E(\lambda, T) d\lambda \]  

Instead of calculating the total radiation emitted by an object, radiation per surface area is more often calculated by using Stefan-Boltzmann’s law 2.7.

\[ \frac{P}{A} = \sigma T^4, \]
where $\sigma = \frac{2\pi^5 \hbar^4}{15c^2h^3} = 5.67 \cdot 10^{-8} Wm^{-2}K^{-4}$ is called the Stefan-Boltzmann constant.

### 2.1.4 Emissivity

Emissivity describes an object’s ability to emit thermal radiation. A black body, that absorbs and emits all of the received radiation, has an emissivity, $\varepsilon = 1$. In reality, black bodies do not exist and thus to be able to calculate the actual emitted radiation, the emissivity of the object needs to be known.

Since emissivity is the ratio of how much radiation a body emits compared to a black body, it is defined by the following equation 2.8:

\[
\varepsilon(\lambda, T, \phi, \theta) = \frac{E(\lambda, T, \varphi, \theta)}{E_{BB}(\lambda, T)},
\]

(2.8)

here $\varphi$ is the azimuthal angle and $\theta$ is the zenith angle. Thus the emissivity is not only changing with wavelength and temperature, but also from the angle in which the object is viewed. A body for which the emissivity changes as a function of wavelength is called a selective emitter, and this is the case for most objects in reality [6].

However it is very hard to find the function for the emissivity for selective emitters. If a narrow spectral band is considered, the emissivity is often seen as being constant with respect to wavelength. In this case the emitter is called a gray body, the assumption that the emissivity is constant for all wavelengths can also be made, known as a gray body assumption.
Kirchoff’s law of thermal radiation (Eq. 2.9) states that the emittance is always equal to the absorptance [16].

\[ \varepsilon(\lambda) = \alpha(\lambda) \]  

This must be true in order to not violate the second law of thermodynamics, which states that heat can not flow from a cold body to a warm body without external work.

### 2.1.5 Atmosphere

The atmosphere is a mixture of gases held on the earth’s surface due to the pull of gravity. The composition of gases in a dry atmosphere can be seen in figure 2.4. Water and ozone are considered being variable gases, the amount of water ranges from 0-4% and ozone ranges from 0.02 to 0.07 ppm [17].

The gravitational force on the atmosphere creates a pressure, making the atmosphere denser at the surface and it gradually thins out with increasing altitude. Due to this, the atmospheres characteristics changes with altitude and therefore different layers of it are defined, as seen in figure 2.5.

Because of the higher density of the troposphere, tropopause, and stratosphere, the most attenuation of the solar radiation occur in these regions. The ozone layer is located in the stratosphere, which absorbs almost all of the UV
2.1. Theory

Figure 2.4: Table of the global average atmospheric constituents for a dry atmosphere [7]

<table>
<thead>
<tr>
<th>Compounds</th>
<th>Formula</th>
<th>Concentration</th>
<th>Total mass (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen</td>
<td>N₂</td>
<td>78.084</td>
<td>3.87 × 10^21</td>
</tr>
<tr>
<td>Oxygen</td>
<td>O₂</td>
<td>20.946</td>
<td>1.19 × 10^21</td>
</tr>
<tr>
<td>Argon</td>
<td>Ar</td>
<td>0.934</td>
<td>6.59 × 10^9</td>
</tr>
</tbody>
</table>

Parts-per-million constituents (ppm = 10^-6 or μL/L)

<table>
<thead>
<tr>
<th>Compounds</th>
<th>Formula</th>
<th>Concentration</th>
<th>Total mass (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon dioxide</td>
<td>CO₂</td>
<td>400</td>
<td>3.11 × 10^14</td>
</tr>
<tr>
<td>Neon</td>
<td>Ne</td>
<td>18.2</td>
<td>6.49 × 10^10</td>
</tr>
<tr>
<td>Helium</td>
<td>He</td>
<td>5.24</td>
<td>3.70 × 10^13</td>
</tr>
<tr>
<td>Methane</td>
<td>CH₄</td>
<td>1.83</td>
<td>5.19 × 10^15</td>
</tr>
<tr>
<td>Krypton</td>
<td>Kr</td>
<td>1.14</td>
<td>1.69 × 10^9</td>
</tr>
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</table>

radiation. On the other hand, almost all of the water vapor can be found in the troposphere, which also have a big impact on the attenuation of the solar radiation.

Besides the gases, the atmosphere also contain particles, known as aerosols. Aerosols are often urban haze, smoke particles, desert dust and sea salt, therefore the amount of aerosols vary both with time and location on the earth, where large cities suffering from smog have considerably more aerosols than rural places. Aerosols are in general estimated to absorb or reflect about 5-10 % of the incoming solar radiation [7].

To measure the total attenuation of radiation through the atmosphere, optical depth is often used as a measure instead of transmittance, which is defined as equation 2.10, where $\tau$ is the atmospheric transmittance.

$$\text{OD} = -\ln \tau$$ (2.10)

Since the attenuation of the radiation increases with the amount of atmosphere the radiation passes through, the air mass (AM) coefficient is defined as the length of the atmosphere column from the ground to the top of the atmosphere, taken in the direction towards the sun.
Figure 2.5: Diagram of the zones of the atmosphere [7]
2.1. Theory

\[ AM = \frac{Y}{X} \]  

(2.11)

Where \( Y \) is the path length through the atmosphere and \( X \) is the path length at zenith. For calculations, a first-order approximation is often used which uses the zenith angle \( \theta \) instead 2.12 [18].

\[ AM \approx \frac{1}{\cos \theta} \]  

(2.12)

Figure 2.6: Figure showing how the length of the path through the atmosphere \( Y \) relates to the zenith angle \( \theta \) [8].

For measuring the amount of aerosols in the atmosphere, a similar measure to the atmospheric optical depth is used. By knowing the transmittance of only the aerosols in a column of atmosphere, \( \tau_{aerosol} \), the aerosol optical depth (AOD) is defined by equation 2.13 [19].

\[ AOD = - \ln \tau_{aerosol} \]  

(2.13)
As for water vapor in the atmosphere, it is measured as precipitable water vapor (PWV) which is defined by equation 2.14.

\[
\text{PWV} = \frac{1}{Dg} \int_{0}^{p_0} \mu(p) dp
\]  

(2.14)

Where D is the mass density of liquid water, g is the gravitational acceleration, \(\mu(p)\) is the mass mixing ratio of water vapor, which describes how the density changes as different gases are mixed in as the pressure changes, and p is the pressure, where \(p_0\) is some surface pressure [20].

Although PWV describes the amount of water vapor in an atmospheric column, the amount of water vapor up to a specific height is also of interest since it is important when calculating the atmospheric transmittance for the different paths described in chapter 2.1.6. To determine the amount of water vapor up to a specific height, the scale height parameter, \(H_w\), is used to describe the rapid decrease of water vapor as an exponential function of elevation. If PWV is known, the scale height is used to extrapolate the amount of water vapor from the ground up to a given height. The amount of water vapor up to height \(H\) is notated as \(w(H)\), and \(w(0)\) is equal to PWV. Then \(w(H)\) can be calculated with equation 2.15 [21].

\[
w(H) = w(0) \exp\left(-\frac{H}{H_w}\right) \approx w(0) \left(1 - \frac{H}{H_w}\right)
\]  

(2.15)

Where \(H_w\) is the scale height, describing how the density of water vapor changes at certain heights. At 300 m, which is approximately the height of the receiver, \(H_w\) is normally taken as \(H_w = 2.5\) km, although this can vary depending on the PWV.

The atmospheric optical depth is shown in figure 2.7. The water absorption bands are clearly visible as the peaks at \(\approx 1.1, 1.4\) and \(1.9 \mu\text{m}\).
2.1. Radiometric chain

The radiometric chain describes the paths the electromagnetic radiation takes to reach the camera. The electromagnetic radiation received by the camera originates from the sun, the receiver and the surrounding environment. The longer the path through the atmosphere is, the more of the radiation is attenuated. It is also dependent on the height, since the water vapor is denser closer to earth, and thus it has a larger effect on the lower heights. An overview of the radiometric chain can be seen in figure 2.8. The calculations below are done for a spectral band $\lambda \in [\lambda_1, \lambda_2]$ since the filter in front of the camera does not transmit other wavelengths.
Three different atmospheric paths are used when calculating the expected radiation received by the camera. Path 1 is from the sun to the heliostats, which are located at ground level (H=0). Path 2 is from the heliostats to the receiver at the top of the tower (height H). Since there is a field consisting of up to several thousand heliostats, the calculation is done for one equivalent heliostat assumed to be located in the middle of the heliostat field. Path 3 is from the receiver to the camera, this path is often similar to path 2 since the camera is located within the heliostat field.

When estimating the total radiation the camera receives, four terms are taken into consideration.

- **Term 1:** Is illustrated as the black line in figure 2.8 and represents the contribution from the receiver. The receiver emits $E_{bb}(\lambda, T_{bb})\varepsilon(\lambda, T_{bb})$ which is transmitted through path 3 with transmittance $\tau_3(\lambda)$. It is then transmitted through the camera lens with a transmittance of $\tau_{lens}(\lambda)$ and the filter with a transmittance $\tau_{filter_i}$, which is explained in further detail in chapter 3.2.2. Subsequently it reaches the camera which has a spectral response $CR_{camera}(\lambda)$. To reduce the amount of variables and increase readability, the total effect of the optics is introduced as one variable $F_i(\lambda)$, defined by equation 2.16

\[
F_i(\lambda) = \tau_{filter_i}(\lambda)\tau_{lens}(\lambda)CR_{camera}(\lambda), \tag{2.16}
\]

where index $i$ specifies the applied filter.

This results in the following camera signal contribution equation 2.17.
2.1. Theory

\[ S_{rec} = \int_{\lambda_1}^{\lambda_2} E_{bb}(\lambda, T_{obj})\varepsilon(\lambda, T_{bb})\tau_3(\lambda)F_i(\lambda)d\lambda \] (2.17)

- **Term 2**: Is illustrated as the yellow line in figure 2.8 and represents the contribution from the sun. The radiation takes path 1 from the sun to the heliostats, which can be considered being located at ground level. The solar radiation in space, \( AM0 \), is gradually attenuated as it passes through the atmosphere and reaches the heliostat at the ground. The transmittance for path 1 will be notated as \( \tau_1(\lambda) \) and thus the solar radiation that reaches the heliostat is \( \tau_1(\lambda)AM0 \). The radiation is then reflected towards the tower by the heliostat with a reflectance \( \rho_{mirror}(\lambda) \). The signal is further attenuated on path 2 with a transmittance \( \tau_2(\lambda) \). It hits the receiver where it gets reflected with the reflectance \( \rho = 1 - \varepsilon(\lambda) \). The reflected radiation then passes through path 3 with transmittance \( \tau_3(\lambda) \), finally it transmit through the filter, and then reaches the camera detector. Since the radiation from the sun is concentrated due to the heliostat field, a concentration factor \( C_x \) is introduced and defined as the ratio between the area of the collected sunlight divided by the area of the receiver. The concentration factor is then multiplied by the integral to compensate for the concentration effect. This results in the camera signal contribution equation 2.18.

\[ S_{sun} = C_x \int_{\lambda_1}^{\lambda_2} (1 - \varepsilon(\lambda, T_{bb}))\tau_1(\lambda)\tau_2(\lambda)\tau_3(\lambda)AM0(\lambda)\rho_{mirror}(\lambda)F_i(\lambda)d\lambda \] (2.18)

- **Term 3**: Is illustrated as the green line in figure 2.8 and represents the contribution from the surroundings. Under the assumption that the emittance from the surrounding objects are negligible since the temperatures of these objects are close to that of the atmosphere, we assume the atmosphere as the only surrounding element which emit \( E_{atm}(\lambda, T_{atm}) \). Since the camera is pointed to the tower; only path 3 needs to be taken into account when calculating the emission the camera receives, described by equation 2.19. Since it is often the case that \( T_{atm} << T_{obj} \), this term can be neglected.
\[
S_{atm} = \int_{\lambda_1}^{\lambda_2} (1 - \tau_3(\lambda)) E_{atm}(\lambda, T_{atm}) F_i(\lambda) d\lambda \tag{2.19}
\]

- **Term 4:** The camera as well as the filter also radiate in the IR spectrum, which generates a contribution to the camera signal, this is shown in figure 2.9. The pink arrow represents the signal from external objects, which have already been accounted for in the previous terms. However the blue and green arrows, representing the filter and camera radiation, have not been accounted for. To minimize this disturbance, the camera is cooled down to \( T = -20^\circ C \), and the filter temperature is usually \( T \sim 25^\circ C \). Compared to the normal operational temperature of the receiver, which is \( T = 300 - 600^\circ C \), the temperatures of the camera and filter are low, thus this term is negligible in comparison to the total signal.

![Figure 2.9: Signal contribution from camera and filter [10]](image)

By adding term 1 (2.17) and term 2 (2.18) under the assumption that term 3 (2.19) and term 4 are negligible, the total estimated camera signal is obtained 2.20.
\[ S_{\text{total}} = S_{\text{rec}} + S_{\text{sun}} \] (2.20)

The relative monochromatic signal contributions are shown in figure 2.10, it clearly shows how term 3 can be neglected. It also shows how the signal is dominated by term 1 at the atmospheric water absorption bands at 1.4\( \mu m \), 1.9\( \mu m \). To make accurate measurements, term 2 should be small since it involves unknown or uncertain parameters such as the concentration factor \( C_x \) and mirror reflectance \( \rho_{\text{mirror}} \). Thus it is suitable to use the signal in the water absorption bands where the total calibration signal is roughly equal to term 1. When the concentrated radiation from the sun does not reach the camera detector due to attenuation, this is referred to as solar blindness [22].

Figure 2.11 shows the relative signal contributions under less favorable conditions. It can be seen that term 2 is contributing to the total signal at 1.4\( \mu m \) and thus the condition of solar blindness is not fulfilled during these conditions.

Figure 2.10: Relative monochromatic signal contributions from term 1, 2 and 3. The filter central wavelengths are shown as the vertical lines at 1.4 and 1.9 \( \mu m \). Transmissions are calculated using SMARTS with AM = 3, PWV = 30 and AOD = 0.1. The temperature of the receiver is set to \( T = 600^\circ C \) and the concentration factor is set to \( C_x = 300 \).
As described in section 1.3, the goal of this thesis is to find suitable conditions for doing the temperature measurement of the receiver. Now with the radiometric chain explained, the goal can be further quantified. Since it is favorable to do the measurement when $S_{\text{total}} \approx S_{\text{rec}}$, a part of the goal is to find how the atmosphere influences these terms and for which set of parameters $S_{\text{sun}} \ll S_{\text{rec}}$ is true. The sensitivity of the terms with respect to small fluctuations in the parameters that affect them will be investigated, as well as the sensitivity of the emissivity measurement. Although solar blindness is a requirement for performing accurate measurements, it is not the only requirement needed. Even under circumstances where $S_{\text{total}} \approx S_{\text{rec}}$, the total signal need to be strong enough to pass through path 3 without being too attenuated by the atmosphere. This will also be studied in this thesis.

2.2 Infrared Thermography

Infrared thermography (IR thermography) is a non-contact measuring technique used to determine the temperature of a surface. A thermal camera is used to capture the infrared radiation emitted by an object. Compared to point measuring contact methods, it carries the advantage of being non-destructive and is
able to generate a complete temperature map of an object. In recent years it has become an increasingly popular temperature measuring method in many industries [23]. However, IR thermography methods are often reliant upon a priori knowledge of the object emissivity. Since the emissivity changes as a function of the object temperature, wavelength and direction of radiation, it is difficult to estimate the emissivity even with some a priori knowledge of it. Therefore it is not as accurate as contact measuring methods and often have an error of 2-5% [24].

2.2.1 Single Color Thermography

Single color thermography is a basic thermography method which measure the radiation in a spectral band. The expected signal is calculated using a black body of known temperature which is then used as a calibration curve to map the generated camera signal to a temperature, this idea is illustrated for two different filters in figure 2.12. Each plot contains a signal curve for a black body and a gray body with emissivity $\varepsilon = 0.5$.

![Figure 2.12: Single color signal curves for two different filters](image)

(a) Filter 1, Central Wavelength (CWL) 1.386 µm
(b) Filter 2, Central Wavelength (CWL) 1.912 µm

The method of calculating the expected camera signal is very similar to the calculations shown in 2.1.6, although those calculations are for the specific application of a solar tower and can not be applied to the general case. The expected received radiation in a more general case is stepwise explained in more detail below, but without considering any atmospheric influence.

By using Planck’s law for black body radiation 2.3, the emitted radiation
can be calculated. Since the body in reality is not a black body, the emissivity $\varepsilon(\lambda, T)$ has to be taken into consideration as well. For a single wavelength measurement, the radiation the body emits is expressed as 2.21.

$$E(T_{obj}, \varepsilon_{obj}, \lambda) = \frac{2\pi hc^2 \varepsilon_{obj}(T_{obj}, \lambda)}{\lambda^5} \frac{e^{\frac{hc}{\lambda k_B T}}}{e^{\frac{hc}{\lambda k_B T}}} - 1$$

(2.21)

Another problem reality brings, is that the measurement has to be done in a spectral band, with an arbitrary bandwidth. The reason for this is that there exists no monochromatic filter that excludes all but one wavelength, as there is a minimal bandwidth. Due to this, the expected radiation that reach the camera is the integral of 2.21 over all wavelengths in the transmission band of the filter $\lambda \in [\lambda_1, \lambda_2]$, which results in 2.22. The filters are explained in further details in section 3.2.2.

$$E(T_{obj}, \varepsilon_{obj}) = \int_{\lambda_1}^{\lambda_2} \frac{2\pi hc^2 \varepsilon_{obj}(T_{obj}, \lambda)}{\lambda^5} \frac{e^{\frac{hc}{\lambda k_B T}}}{e^{\frac{hc}{\lambda k_B T}}} d\lambda - 1$$

(2.22)

As done in the section about the radiometric chain 2.1.6, the term corresponding to the influence of the optics, $F_i(\lambda)$, defined as 2.16, also have to be considered to get the complete camera signal. Furthermore the atmosphere plays a crucial role when performing infrared thermography on long distances. In this case, the path from the tower to the camera is a few hundred meters, making attenuation loss important to take into account. Thus the atmospheric transmittance, $\tau(\lambda)$ also has to be taken into account in the calibration signal. The final calibration signal, notated as $S_{sc}(T_{obj}, \varepsilon_{obj}, \tau)$ is then described by the following equation 2.23.

$$S_{sc}(T_{obj}, \varepsilon_{obj}, \tau) = \int_{\lambda_1}^{\lambda_2} \varepsilon_{obj}(T_{obj}, \lambda) \tau(\lambda) E(T_{obj}, \lambda) F_i(\lambda) d\lambda$$

(2.23)

Where $E(T_{obj}, \lambda)$ is defined by Planck’s law 2.3.
If the emittance and atmospheric transmittance are known, this equation is a one-to-one mapping between temperature and camera signal. Accordingly, when measuring the received radiation, it is possible to find which point on the calibration curve that matches the actual measurement, and then find which temperature this corresponds to, as illustrated in figure 2.13.

![Filter-1386 calibration curve](image)

Figure 2.13: Calibration curve for single color thermography, showing how the intersection between the measured signal and calibration curve is used for finding the temperature. The calibration curve uses $\varepsilon \tau = 0.7$.

However, as seen in equation 2.23, this method is dependent on the a priori knowledge of the object emittance and atmospheric transmittance, which is a problem in many cases. A method that intends to solve this problem is ratio thermography, also known as dual color thermography, since it uses two spectral bands instead of one.

### 2.2.2 Dual Color Thermography

The idea of dual color thermography, also called ratio thermography, is to calculate the ratio of two spectral band measurements. By choosing these bands
close to each other, such that \( \varepsilon_{\text{obj}}(T_{\text{obj}}, \lambda_i)\tau(\lambda_i) \approx \varepsilon_{\text{obj}}(T_{\text{obj}}, \lambda_j)\tau(\lambda_j) \) and assuming that \( \varepsilon_{\text{obj}}(T_{\text{obj}}, \lambda_k)\tau(\lambda_k) \) stays constant within each band, the emissivity and transmittance can be seen as constants in the integral and thus it can be canceled out in the ratio. Under this assumption, known as gray body assumption, ratio thermography is independent of any knowledge about the emissivity and transmittance. The equation for this is derived below.

In the monochromatic case, that is for one wavelength, an analytical expression for the temperature as a function of the ratio can also be derived, as shown in appendix A. However this is only possible in theory, in practice the broader transmission band of the filter makes monochromatic measurements impossible, as previously mentioned. Hence a calibration curve has to be used for this method too. A few more steps are also necessary for this method and these will be described at the end of the chapter.

**Gray body assumption**

By taking the ratio of two measurements, for \( \lambda_i \in [\lambda_1, \lambda_2] \), and \( \lambda_j \in [\lambda_3, \lambda_4] \), where each measurement is described by 2.23, we get 2.24.

\[
S_{dc}(T_{\text{obj}}, \varepsilon_{\text{obj}}, \tau) = \frac{\int_{\lambda_1}^{\lambda_2} \varepsilon_{\text{obj}}(T_{\text{obj}}, \lambda)\tau(\lambda)E(T_{\text{obj}}, \lambda)F_i(\lambda)d\lambda}{\int_{\lambda_3}^{\lambda_4} \varepsilon_{\text{obj}}(T_{\text{obj}}, \lambda)\tau(\lambda)E(T_{\text{obj}}, \lambda)F_j(\lambda)d\lambda}
\]

(2.24)

By making the assumption that \( \varepsilon_{\text{obj}}(T_{\text{obj}}, \lambda_{1,2})\tau(\lambda_{1,2}) \approx \varepsilon_{\text{obj}}(T_{\text{obj}}, \lambda_{3,4})\tau(\lambda_{3,4}) \) and that these are also constant within the limits of the integrals, \( \varepsilon_{\text{obj}}(T_{\text{obj}}, \lambda)\tau(\lambda) \) can be canceled out, resulting in 2.25.
2.2. Infrared Thermography

\[ S_{dc}(T_{obj}) = \frac{\int_{\lambda_1}^{\lambda_2} E(T_{obj}, \lambda) F_i(\lambda) d\lambda}{\int_{\lambda_3}^{\lambda_4} E(T_{obj}, \lambda) F_j(\lambda) d\lambda} \]

Which is independent of the emissivity and transmittance. The ratio calibration curve is shown in figure 2.14

Using the estimated temperature from the ratio calibration curve, \( T_{dc} \), the product \((\varepsilon \tau)_k\) can also be estimated for each filter band. This is done by calculating for a given filter the ratio between the measured signal \( S_{meas}(T_{dc}) \), and the expected signal a black body with temperature \( T_{dc} \) would generate under no atmospheric influence, \( S_{sc}(T_{dc}) \). This ratio is equal to \((\varepsilon \tau)_k\), since \( \varepsilon_{obj}(T_{obj}, \lambda) \tau(\lambda) = 1 \) for the black body with no atmospheric influence. It is
still assumed that the receiver and atmosphere are gray within each filter band, thus the product is not dependent on the wavelength and is described by equation 2.26 [25]. This idea is illustrated in figure 2.15.

\[ \varepsilon \tau_k = \frac{S_{meas}(T_{dc})_k}{S_{sc}(T_{dc})_k|\varepsilon \tau = 1} \]  

(2.26)

This is done for both filters, so that \((\varepsilon \tau)_i\) and \((\varepsilon \tau)_j\) are obtained. If any a priori knowledge of the atmospheric transmittance exist, the emissivity for each filter band can be further estimated.

By applying this method to the measurement signal 2.20 derived for the radiometric chain, it is theoretically possible to do the temperature measurement for a solar tower without a priori knowledge of the emittance of the receiver and atmospheric transmittance. If a priori knowledge of the atmospheric transmittance exists, it is also possible to estimate the emittance of the receiver. This method is using the gray body assumption, but if a priori knowledge exist this can be used to compensate for the gray body assumption.
2.2. Infrared Thermography

**Gray body compensation**

To compensate for the gray body assumption, the compensation factor $k$ is introduced and defined by equation 2.27.

\[
k = \frac{(\varepsilon \tau)_j}{(\varepsilon \tau)_i} \neq 1
\]

(2.27)

Some a priori knowledge of the coating emittance and atmospheric transmittance is necessary to compute the compensation factor. A priori knowledge of the atmospheric transmittance can be derived with SMARTS, which is explained in section 3.2.3, and data about the receiver coating can be obtained by making spectrophotometric measurements in an optical laboratory. The receiver coating used for the solar tower used in this thesis has been proven to be nearly gray which means that the gray body assumption for the receiver is accurate. With this a priori knowledge the emissivity ratio cancels out and using the transmittance from SMARTS the compensation factor is a known value calculated by equation 2.28.

\[
k = \frac{(\tau)_j}{(\tau)_i} \neq 1
\]

(2.28)

The temperature measurement is now done by projecting the compensated ratio signal, 2.29, onto the same calibration curve that is derived in the previous section 2.25. An illustration of this is seen in figure 2.16.

\[
SR_{comp} = kSR_{meas} = k \frac{S_{meas}(T_{obj})_i}{S_{meas}(T_{obj})_j}
\]

(2.29)
Figure 2.16: Calibration curve for ratio thermography with $k > 1$. The difference between $SR_{comp}$ and $SR_{meas}$ is exaggerated for illustration purposes.

Using the temperature from the compensated measurement, $T_{dc,comp}$, the value of the emittance and transmittance within each filter band can be calculated in the same way as they are calculated in the gray body assumption method 2.26.
Chapter 3

Methodology

In this chapter the methodology used to obtain the results is explained. An overview of the simulation tool is given and then each part of it is explained in further details.

3.1 Acknowledgement of the used Software

All of the simulations done in this thesis are written in MATLAB® version 2021b, a programming language and environment developed by MathWorks. An external simulation tool, Simple Model of the Atmospheric Radiative Transfer of Sunshine (SMARTS) is integrated into the MATLAB® toolbox to simulate the atmospheric transmittance. SMARTS is developed by Dr. Christian Gueymard and the version used in this thesis is SMARTS 2.9.8.1.

3.2 Modelling Approach

The entire setup described in chapter 2.1.6 and shown in figure 2.8 is simulated in MATLAB® and SMARTS is used to compute the atmospheric transmission coefficients. The main script is a MATLAB live script, which calls on several live functions, the advantage of using a live script is that the output is stored and displayed alongside the code that creates it. Most of the data is stored and passed through the functions as vectors or structures. A flowchart of the simulation tool can be seen in figure 3.1.

A local database is used to store data about mirror reflectance, camera detector response, receiver coating absorption etc. The filter transmission curves
are also modeled as gaussian functions and stored in the database. A configuration file containing the user input is used to read the relevant parameters from the database and store them as variables. The spectral resolution is also defined here, which is 1 \text{ nm} and the wavelength ranges from 0.8 \text{ \mu m} to 2.5 \text{ \mu m}. SMARTS is used to generate the transmittance for the paths shown in figure 2.8. The data for the scenario given by the user is passed to the function problem setup, which is a live function used to formulate and solve the forward problem, i.e. calculate the calibration curves and simulate the signal read by the camera. This task is in turn split into four different functions, as seen in 3.1. The camera setup evaluates the filter models to get the filter transmittance, which is used to get the optical response $F_i$ and single color calibration signal later computed in the filter calibration function. The optical response is used together with the radiometric terms to define the forward problem, which simulates the actual signal the camera receives. This is later used together with the ratio calibration to infer the temperature and emissivity in the inverse problem solver function. One simulation takes approximately 1.2 seconds to run if no visualization is used.

To determine the influence of the atmosphere, the simulation is run a couple of thousand times for different inputs. Several batches of inputs are defined with different ranges, a design of experiments is set up by using a full factorial design. MATLAB’s® function for this is used to get every combination of inputs to generate a batch. The results for each batch is saved as .M files and later visualized and interpreted. The range of inputs used for each batch will be explained in the results.
3.2. Modelling Approach

Figure 3.1: Flowchart of simulation toolbox
3.2.1 Configuration and Database

The configuration file is used to define the environment for the measurement, the user sets the values of the atmospheric parameters, tower characteristics, type of mirror and type of camera. SMARTS is then used with the given atmospheric parameters to calculate the transmittance for the different paths as well as the extraterrestrial spectrum. The parameters defined and set in the configuration file are shown in table 3.1.

<table>
<thead>
<tr>
<th>Parameters in configuration file</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toolbox configuration</td>
</tr>
<tr>
<td>Camera</td>
</tr>
<tr>
<td>Power plant</td>
</tr>
<tr>
<td>Atmosphere</td>
</tr>
<tr>
<td>Wavelength vector</td>
</tr>
<tr>
<td>Temperature calibration interval</td>
</tr>
<tr>
<td>Filter model</td>
</tr>
<tr>
<td>Chip ID</td>
</tr>
<tr>
<td>Lens ID</td>
</tr>
<tr>
<td>Filter ID</td>
</tr>
<tr>
<td>Chip temperature</td>
</tr>
<tr>
<td>Cx</td>
</tr>
<tr>
<td>Absorber temperature</td>
</tr>
<tr>
<td>Tower height</td>
</tr>
<tr>
<td>Length path 2</td>
</tr>
<tr>
<td>Length path 3</td>
</tr>
<tr>
<td>Absorber ID</td>
</tr>
<tr>
<td>Site longitude</td>
</tr>
<tr>
<td>Site latitude</td>
</tr>
<tr>
<td>Site altitude</td>
</tr>
<tr>
<td>Mirror ID</td>
</tr>
<tr>
<td>Absorber ID</td>
</tr>
<tr>
<td>AM</td>
</tr>
<tr>
<td>PWV</td>
</tr>
<tr>
<td>AOD</td>
</tr>
<tr>
<td>H_W</td>
</tr>
<tr>
<td>Site longitude</td>
</tr>
<tr>
<td>Temperature calibration interval</td>
</tr>
<tr>
<td>Filter model</td>
</tr>
<tr>
<td>Chip temperature</td>
</tr>
<tr>
<td>Wavelength vector = [0.8:10−3:2.5] µm</td>
</tr>
<tr>
<td>Temperature calibration interval = [50:5:1000] °C</td>
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<tr>
<td>Filter model = Measured data</td>
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<tr>
<td>Chip ID = G14673_0808W</td>
</tr>
<tr>
<td>Lens ID = OPTEC</td>
</tr>
<tr>
<td>Filter ID = All filters</td>
</tr>
<tr>
<td>Chip temperature = -20°C</td>
</tr>
<tr>
<td>Site longitude = 2.35818</td>
</tr>
<tr>
<td>Site latitude = 37.09076</td>
</tr>
<tr>
<td>Site altitude = 0.5 km</td>
</tr>
<tr>
<td>Mirror ID = Custom mirror</td>
</tr>
<tr>
<td>Absorber ID = Pyromark 2500</td>
</tr>
</tbody>
</table>

Table 3.1: Configuration parameters. Gray parameters vary between simulations while white colored parameters stay fixed.

<table>
<thead>
<tr>
<th>Fixed parameter values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toolbox configuration</td>
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<tr>
<td>Camera</td>
</tr>
<tr>
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<tr>
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<td>Chip ID = G14673_0808W</td>
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<tr>
<td>Lens ID = OPTEC</td>
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<tr>
<td>Filter ID = All filters</td>
</tr>
<tr>
<td>Chip temperature = -20°C</td>
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<tr>
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<tr>
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</tr>
<tr>
<td>Mirror ID = Custom mirror</td>
</tr>
<tr>
<td>Absorber ID = Pyromark 2500</td>
</tr>
</tbody>
</table>

Table 3.2: Fixed parameter values. Site coordinates are for the Tabernas desert located outside of Almería, Spain.

The database is a local database that consists of several csv and xlsx files containing data about the following:

- Mirror spectral reflectance: Only one type of mirror is stored in the database.
3.2. Modelling Approach

- Absorber surface spectral absorption: Two types of absorbers are stored, Pyromark 2500 and Haynes 230 (oxidized), they are both near gray bodies. Their spectral absorption is stored for 7 different types of exposure, although the only exposure used is 1000 hours at 800°C.

- Camera detector response: Only one type of camera is stored, that is from Hamamatsu and has a spectral response in the range 1.3-2.15 \( \mu m \) \cite{26}. The spectral detector response is read from the database and converted to spectral quantum efficiency.

- Camera lens transmittance: Only one type of lens is stored in the database, it has a focal length of 100 mm and works in the spectral range 0.9-2.3 \( \mu m \) \cite{27}.

- Filter transmittance: 4 different filters are stored in the filter database. These are modeled using several different equations which are explained in the filter section 3.2.2. The models are stored in the database and the model is specified in the configuration file so that just one model is read and stored when fetching the data.

Figure 3.2 shows the data read from the database. The filter transmittance is the raw data without any applied model. The absorber reflectance is shown although the absorption is used in the calculations instead, obtained by \( \alpha = 1 - \rho \).
(a) Absorber and mirror reflectance  
(b) Camera spectral response and quantum efficiency

(c) Lens transmittance  
(d) Filter transmittance

Figure 3.2: Spectral properties of the parameters stored in the database

For each data type an ID is specified in the configuration file, which is used to read the relevant data. The data is stored as two vectors, one for the spectral properties and one for the corresponding wavelengths, these are interpolated with the wavelength vector specified in the configuration file to get the correct resolution and interval.

3.2.2 Filter Modelling

Four different filters manufactured by Spectrogon AB are used in the simulation. These are all narrow bandpass filters, which is defined by Spectrogon as having a half width at less than 3% of the central wavelength (CWL) [28]. I.e. the transmittance at $\pm 3\%$ of the CWL is less than 50% of the transmittance at the CWL. The filters used have a CWL of 1.386, 1.640, 1.912 and 2.090 $\mu$m. Spectrogon AB has supplied information regarding CWL, HW and peak transmittance, $\tau_{\text{peak}}$, of each filter along with data sheets containing complete spectral transmittance measurements, which is also the data that is stored in
the filter database.

Instead of using the raw data, three models are used to fit the data. Using the models reduces the time it takes to read the measured data from the database, since the model is a more compact way of storing the data. As shown in figure 3.2d, the measured data shows that the filter transmittance follows a bell curve, and thus its suitable to model it with gaussian functions. The evaluated functions are a gaussian 3.1 function fitted to the data, a generalized gaussian function 3.2 fitted to the data, and a gaussian not fitted to the data but use the specified CWL, HW and $\tau_{peak}$ as parameter values in the model instead. These are compared to the raw data, table 3.3 shows the RMSE for each model and figure 3.3 is a graphical representation of the filter models. As seen in these representations, the model using Spectrogon specified CWL, HW and $\tau_{peak}$ differ slightly from the measured data for each filter. Hence using the models fitted by the measured data gives a more accurate simulation. Table 3.4 shows the values of the fitted variables for each model and filter.

\[
f(x) = a \exp\left(-\frac{(x-b)^2}{2c^2}\right)
\]  

(3.1)

\[
f(x) = a \exp\left(-\left(\frac{(x-b)^2}{2c^2}\right)^P\right),
\]

(3.2)

where $a$ is the peak height of the function which equals peak transmittance, $b$ is the center of the bell curve which equals the CWL and $2\sqrt{2\ln 2}c \approx 2.355c$ is the HW. The generalized gaussian includes another parameter $P$, which is used to flatten the peak of the curve. A higher value of $P$ gives a broader peak and since HW remains the same, this leads to a steeper slope as well.
Chapter 3. Methodology

Figure 3.3: Filter models

<table>
<thead>
<tr>
<th>Filter names</th>
<th>Gaussian</th>
<th>Generalized gaussian</th>
<th>Spectrogram gaussian</th>
</tr>
</thead>
<tbody>
<tr>
<td>$NB_{1386}$</td>
<td>0.2399</td>
<td>0.1817</td>
<td>0.5519</td>
</tr>
<tr>
<td>$NB_{1640}$</td>
<td>0.6238</td>
<td>0.4129</td>
<td>1.4108</td>
</tr>
<tr>
<td>$NB_{1912}$</td>
<td>0.2169</td>
<td>0.1945</td>
<td>0.5523</td>
</tr>
<tr>
<td>$NB_{2090}$</td>
<td>0.5735</td>
<td>0.3705</td>
<td>1.1635</td>
</tr>
</tbody>
</table>

Table 3.3: RMSE values for the models
### 3.2. Modelling Approach

**Parameter values:** \( a = \tau_{\text{peak}} \); \( b = \text{CWL} \); \( c = \frac{HW}{2.355} \); \( P = \text{Flatness} \)

<table>
<thead>
<tr>
<th>Filter names</th>
<th>Gaussian</th>
<th>Generalized gaussian</th>
<th>Spectrogon gaussian</th>
</tr>
</thead>
<tbody>
<tr>
<td>( NB_{1386} )</td>
<td>( a = 74.4 ) ( b = 1390.7 ) ( c = 5.9 )</td>
<td>( a = 71.7 ) ( b = 1390.7 ) ( c = 6.0 ) ( P = 2.4 )</td>
<td>( a = 71.5 ) ( b = 1390.0 ) ( c = 4.2 )</td>
</tr>
<tr>
<td>( NB_{1640} )</td>
<td>( a = 93.7 ) ( b = 1642.1 ) ( c = 12.4 )</td>
<td>( a = 88.5 ) ( b = 1642.1 ) ( c = 12.7 ) ( P = 2.7 )</td>
<td>( a = 90.1 ) ( b = 1640.0 ) ( c = 9.3 )</td>
</tr>
<tr>
<td>( NB_{1912} )</td>
<td>( a = 82.3 ) ( b = 1910.4 ) ( c = 6.6 )</td>
<td>( a = 80.6 ) ( b = 1910.4 ) ( c = 6.6 ) ( P = 2.2 )</td>
<td>( a = 73.8 ) ( b = 1910.0 ) ( c = 4.8 )</td>
</tr>
<tr>
<td>( NB_{2090} )</td>
<td>( a = 83.7 ) ( b = 2088.1 ) ( c = 13.7 )</td>
<td>( a = 79.0 ) ( b = 2088.1 ) ( c = 13.9 ) ( P = 2.7 )</td>
<td>( a = 92.0 ) ( b = 2088 ) ( c = 10.3 )</td>
</tr>
</tbody>
</table>

*Table 3.4: Parameter values for models*
3.2.3 SMARTS

SMARTS (Simple Model of the Atmospheric Radiative Transfer of Sunshine) is a program developed by Dr. Christian Gueymard, which is used to compute clear sky spectral irradiances given specified atmospheric conditions [29]. The computed spectral irradiance is used to determine the atmospheric transmittance for the radiometric paths.

SMARTS uses parameters defined by the user in the configuration file, but also uses several other parameters defined inside the SMARTS script. The inputs required from the configuration file are: PWV, $H_W$, AM, AOD, site location, path range, tower height and azimuth. The parameters set in the SMARTS script are atmospheric pressure, season and type of atmosphere, although these are fixed to 1.013 hPa, summer and desert respectively. For specifying the solar geometry, different inputs can be used. These are AM, zenith and azimuth angles, elevation and zenith angle, or date, time and location. For this application AM is used to calculate the spectral irradiance for path 1, while elevation ($\phi$) and zenith ($\theta$) angles, computed from the tower height and slant ranges as seen in 3.3 and 3.4, are used to calculate the spectral irradiance for path 2 and 3.

\[
\theta = 90 - \arcsin\left(\frac{\text{tower height}}{\text{length path}}\right) \quad (3.3)
\]

\[
\phi = |90 - \theta| \quad (3.4)
\]

The atmospheric transmittance for path 1 is calculated by dividing the spectral irradiance at the ground with the extraterrestrial spectrum. For path 2 and 3 a concept known as the fictitious sun is used, this concept is illustrated in figure 3.4 [21]. The idea is to introduce a fictitious sun aligned with the path for which the transmittance is to be calculated. Using the fictitious sun method for path 2, SMARTS is used once to compute the spectral irradiance at the tower, and once more for the spectral irradiance at the mirror. The atmospheric transmittance for path 2 is then calculated as \(\tau_{\text{path2}} = \frac{E'_{M}}{E'_{T}}\). The same concept is used for path 3, with the difference that the second calculation computes the spectral irradiance at the camera, \(E'_{C}\) instead of \(E'_{M}\), the transmittance is then derived the same way as for path 2. Thus SMARTS is used 5 times for each simulation, one calculation takes approximately 0.063 seconds resulting in a total of 0.315 seconds per simulation.
The source code for SMARTS is available online for free \cite{29}, but this is not available in the simulation toolbox and thus it can be seen as a black box system.

### 3.2.4 Problem setup

The problem setup function is the main function for simulating the scenario and compute the calibration curves. This function calls the set of subfunctions described below.

**Camera Setup**

The camera setup is a short function that uses the wavelength vector to evaluate the chosen filter model function for each filter and returns the filter transmittance, $\tau_{filter\_i}$, and $CW_{Li}$. 

---

Figure 3.4: Fictitious sun concept illustrated for computing the transmittance for path 2.
Filter Calibration

The filter calibration function uses Planck’s law to calculate the spectral density of black body radiation for every temperature in the temperature calibration interval. The total camera spectral response \( F_i(\lambda) \) is also computed here which together with the spectral density is used to derive the calibration signal with \( \varepsilon \tau = 1 \). This is done once for each filter.

\[
\text{Temperature calibration interval, } T_{\text{calib}} \\
\tau_{\text{lens}} \\
\tau_{\text{filter}} \\
\text{Camera QE} \\
\text{Wavelength vector}
\]

\[
E_{\text{bb, calib}} = \text{Planck}(T_{\text{calib}})
\]

\[
F_i = \tau_{\text{lens}} \tau_{\text{filter}} \text{QE}
\]

\[
\text{Monochromatic calibration signal} = E_{\text{bb, calib}} \cdot F_i
\]

\[
\text{Calibration signal} = \int_{\lambda} E_{\text{bb, calib}} \cdot F_i \, d\lambda
\]

Figure 3.5: Flowchart for filter calibration function
3.2. Modelling Approach

**Ratio Calibration**

The ratio calibration derives the ratio calibration curve, defined as 2.24, using the single color calibration signals derived in the filter calibration function. Several ratios are computed, but only the ratio between filter 1 (CWL = 1.386) and filter 3 (CWL = 1.912) is used later, we call this ratio A.

![Flowchart for ratio calibration function](image)

Figure 3.6: Flowchart for ratio calibration function
Radiometric Chain

Here the radiometric terms described by the equations 2.17, 2.18, 2.19 and 2.20 in chapter 2.1.6 are computed. The spectral density of radiation is computed for the absorber and atmosphere. Each term is divided by the sum of all terms to get the contribution of each term in the total signal.

Figure 3.7: Flowchart for radiometric chain function
Forward Problem

The forward problem is supposed to simulate the real scenario, having access to detailed spectral knowledge. The signal measured by the camera is simulated as the integral of the total radiometric signal, computed in the radiometric chain function, multiplied with the total camera spectral response, $F_i(\lambda)$. Reference band values for $\varepsilon$, $\tau$ and $\varepsilon\tau$ are also computed as the ratio between a black body signal and the signal for a gray receiver, gray atmosphere and gray receiver and gray atmosphere respectively, this is done for each filter.

Figure 3.8: Flowchart for forward problem function
3.2.5 Inverse problem solver

The inverse problem solver uses the theory in section 2.2 to estimate the temperature and emissivity. Three different methods of dual thermography are used:

- Method 1: Uses the gray body assumption for both receiver and atmosphere.

- Method 2: Uses the a priori knowledge from the forward problem to compensate for both the receiver and atmosphere.

- Method 3: Uses the a priori knowledge from SMARTS to compensate for the atmospheric transmittance, assumes receiver to be gray.

The reference emissivity computed in the forward problem and receiver temperature set in the configuration file are used to compute the temperature and emissivity errors. Note that the emittance estimation is done for both filters in the ratio.
3.2. Modelling Approach

Figure 3.9: Flowchart for inverse problem solver function
3.3 Batch simulation approach

To run several simulations, the user defines a range of inputs. A full factorial design is used to generate a configuration for every combination of inputs in the defined ranges. Each configuration is then simulated and the results are saved for visualization and interpretation. Since one simulation takes approximately 1.5 seconds to run, some inputs have to stay fixed in each batch to limit the number of simulations and thus also the time it takes to run the batch. Instead, several different batches are run, where each batch focuses on a specific set of inputs. This limits the information about how certain inputs interact with each other, but greatly reduces the simulation time from what would be months if all combinations where used, to a total of 10-15 hours.

The batches are constructed to extract information about two different subproblems. The first is to find which inputs have the largest influence on the results and for which set of inputs solar blindness is achieved. The second subproblem is to find how sensitive the measurement accuracy is to small fluctuations in the most influential inputs, once solar blind conditions are fulfilled. The configured batches used to extract the information are:

- **General screening 1**, a coarse grid is used to investigate the effect of the following inputs:
  - AM
  - PWV
  - Absorber temperature
  - Cx

- **General screening 2**, a coarse grid is used to investigate the effect the following inputs:
  - Tower height
  - Length path 2
  - Length path 3
  - Aerosol depth
  - Atmospheric temperature

- **τ analysis**, a coarse grid is used to evaluate how the atmospheric parameters affect the τ slope:
  - AM
  - PWV
  - Aerosol depth
  - Scale height

- **Sensitivity analysis**, a very fine grid is used to evaluate how the results are affected by small fluctuations in the following inputs:
  - AM
  - PWV
Chapter 4

Results and Discussion

In this chapter the results from the batch simulations are shown and interpreted to answer the two main questions of the thesis, under which conditions is solar blindness fulfilled and once fulfilled, how sensitive is the measurement accuracy to small fluctuations in the atmospheric parameters. Other important parameters related to the power plant are also investigated, to determine which other criteria have to be fulfilled to make accurate measurements.

In chapter 2.1.6 solar blindness is assumed when $S_{sun} \approx 0$, however here we introduce two new indirect metrics of solar blind conditions. If $OD < -3$ for both narrow bandpass filters, from the definition of optical depth we get that $\tau_3 < 10^{-3}$, and thus 0.1 % of the solar radiation in that spectral band reach the ground, we will then assume solar blind conditions are nearly achieved. The other metric use the a posteriori knowledge of the temperature error to determine whether the measurement was done under solar blind conditions or not. The temperature error is derived using method 2, described by equation 2.29 with $k$ compensating for both atmospheric transmittance and absorber emittance. When the error is below 2 % of the absorber temperature in Kelvins, we assume there is not much noise in the signal and therefore the sun does not influence the signal. Using the measure of optical depth makes it easier to relate solar blind conditions to the atmospheric parameters, since the optical depth is directly a function of the atmosphere. The temperature error threshold is used to filter out the measurements made under favorable conditions and from there determine what those conditions are. By varying this threshold the sensitivity of each method will also be analyzed.
4.1 Screening of parameters

The first batch is a general screening of the parameters thought to have the largest impact on the measurement. Figure 4.1 shows the ratio of solar blind measurements for each parameter where the value varies over the range, which can be seen in table 4.1. AM has a finer resolution for low values, since low values are more commonly seen throughout the day due to AM being a function of the zenith angle. For example a zenith angle, $\theta = 0^\circ$ corresponds to $AM = 1$ and $\theta = 60^\circ$ corresponds to $AM = 2$.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Start:Step:Stop</th>
</tr>
</thead>
<tbody>
<tr>
<td>$AM$</td>
<td>[1:0.1:1.5 2:1:5]</td>
</tr>
<tr>
<td>$PWV$</td>
<td>[5:5:30]</td>
</tr>
<tr>
<td>$T_{abs}$</td>
<td>[35:50:650]</td>
</tr>
<tr>
<td>$Cx$</td>
<td>[200:100:1000]</td>
</tr>
</tbody>
</table>

Table 4.1: Parameter range for values in screening batch 1
4.1. Screening of parameters

4.1.1. Air mass (AM)

From figures 4.1a-4.1b it can be seen that it is favorable to have a high AM as well as PWV. A higher AM and PWV attenuates the solar radiation more on path 1 and thus less of it interferes with the signal $S_{rec}$. The small drop of solar blind measurements for higher PWV is likely due to the attenuation on path 3 being too high and therefore the radiation from the absorber also gets attenuated. Even though PWV is rarely above 30 mm, it is likely that this pattern continues for higher values.

As seen in figure 4.1c, a low Cx leads to more accurate measurements since less radiation is concentrated on the tower and thus less radiation is reflected off the tower onto the camera. An important observation from figure 4.1d, is that no measurements have an error less than 2% when the absorber temperature is...
below 450°C, which shows a crucial limit to the measurement technique. Even at 450°C the conditions need to be very favorable to make accurate measurements.

Further information from the first screening batch can be extracted from figure 4.2, where the interactions between the parameters are shown.

As seen in figure 4.2a, with a low AM and PWV = 5 no measurements are solar blind, that is if the atmosphere is very dry no measurements can be
made during mid day. On the other hand, if the absorber temperature is above 550°C, accurate measurements can always be done when the sun is low, that is for a zenith angle above $\theta > 75^\circ$. A similar conclusion can be drawn from figures 4.2c-4.2e, if PWV $> 15$ mm or AM $> 4$, accurate measurements can always be done if the absorber temperature is above 600°C, although it is rare that the absorber reaches those temperatures.

Figure 4.3 confirms the measurement threshold stated in the introduction of this chapter, that optical depths below -3 gives more accurate measurements. However since the absorber temperature and concentration factor also plays a crucial role in making accurate measurements, optical depths below -3 does not guarantee accurate measurements. These results also shows that a lower optical depth is obtained for filter 1, i.e at $\approx 1.4\mu m$, thus filter 1 is more critical for accurate measurements. Here it is also worth noting that the optical depths are correlated and no measurements at all are done for some combinations of the optical depths.

Figure 4.3: Percent of solar blind measurements as function of optical depth
Figure 4.4 illustrates how the optical depth varies with AM and PWV and the red line in the contour plots illustrate the limit of -3. Using the MATLAB function `stepwiselm`, a polynomial regression is used to fit a model to the data for each filter. The models are described by equation 4.1 and the coefficient values and goodness of fit for the models are displayed in tables 4.2-4.3. The P-values for all the listed coefficients are 0, showing that all coefficients are necessary for the model to fit the data.

\[
\text{Optical depth} = \beta_0 + \beta_1 AM + \beta_2 PWV + \beta_3 AM \cdot PWV + \beta_4 AM^2 + \beta_5 PWV^2 
\]

(4.1)

Figure 4.4: Optical depths as function of AM and PWV
4.1. Screening of parameters

The second screening batch contain parameters predicted to have less impact on the measurement accuracy. These are path 2 and 3 length, aerosol depth, atmospheric temperature and tower height, and the ranges for these are displayed in table 4.4. The results show that these parameters have negligible impact on the accuracy. Therefore any figures of these results are omitted in this thesis.

<table>
<thead>
<tr>
<th>Parameter ranges, batch 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>-----------</td>
</tr>
<tr>
<td>Path2</td>
</tr>
<tr>
<td>Path3</td>
</tr>
<tr>
<td>AOD</td>
</tr>
<tr>
<td>T atm</td>
</tr>
<tr>
<td>Tower height</td>
</tr>
</tbody>
</table>

Table 4.4: Parameter range for values in screening batch 2
4.2 Method comparison

The temperature errors for the three different methods previously explained in chapters 2.2 and 3.2.5 are visualized as boxplots in figure 4.5.

Figure 4.5: Method comparison for different thresholds

The red line indicates the median temperature error and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme data points not considered outliers, and the outliers are shown as ‘+’. The methods achieve similar accuracy when considering errors of 2%, but as this threshold decreases method 2 and 3 performs better than method 1. Since the 2% threshold is the standard accuracy for most thermography applications, the atmospheric compensation factor do not seem
to have any significant effect unless very precise measurements have to be made.

As the temperature measurement is used to estimate the emissivity of the receiver, we also analyze how the emissivity error relates to the temperature error. Figure 4.6 shows this relation for both filters, where the lower figures are zoomed in on temperature errors below 2%.

Filter 3 shows an almost linear relation under solar blind conditions whereas filter 1 have a more scattered relation, indicating that there is more noise passing through filter 1 than filter 3.
To further compare the different methods used, we investigate how the compensation factor, $\tau$ slope, correlates to the temperature error. This is shown in figure 4.7, where the illustration to the right is zoomed in on solar blind measurements. The temperature error for method 1 starts deviating from the other methods as the compensation factor increases, which is expected since this method does not use it to compensate for the atmospheric influence.

Due to the lack of atmospheric compensation, method 1 tends to underestimate the temperature as the $\tau$ slope increases, while the other methods always seem to slightly overestimate it. However the absolute temperature error difference between the methods is small, as already illustrated in figure 4.5.
4.3 Sensitivity and $\tau$ slope analysis

Furthermore a batch containing the atmospheric parameters with ranges seen in table 4.5 is run. The resulting figure 4.8 illustrates how the compensation factor depends on the atmospheric parameters. From figures 4.8a-4.8b it is proven that AM have no impact and for a fixed scale height the $\tau$ slope is just a function of PWV, as also shown by the fitted model equation 4.2. Although the scale height shows to impact the $\tau$ slope, the effect is smaller than that of PWV. Especially since the range of the scale height can be considered more extreme, due to the normal variation rarely exceeding the interval 1.75-3.75, as described in [21].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Start:Step:Stop</th>
</tr>
</thead>
<tbody>
<tr>
<td>$AM$</td>
<td>[1:1:5]</td>
</tr>
<tr>
<td>$PWV$</td>
<td>[5:5:30]</td>
</tr>
<tr>
<td>$AOD$</td>
<td>[0:0.1:0.2]</td>
</tr>
<tr>
<td>Scale height</td>
<td>[1:0.5:5]</td>
</tr>
</tbody>
</table>

Table 4.5: Parameter range for values in $\tau$ slope analysis batch
Figure 4.8: Parameter interactions

\[ \tau_{slope} = \beta_0 + \beta_1 PWV \]  

(4.2)

<table>
<thead>
<tr>
<th>Model ( \tau_{slope} ): RMSE = 0.0014</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient</td>
</tr>
<tr>
<td>( \beta_0 )</td>
</tr>
<tr>
<td>( \beta_1 )</td>
</tr>
</tbody>
</table>

Table 4.6: Coefficients for model of \( \tau \) slope
Lastly the sensitivity of the measurements with respect to AM and PWV is analyzed, with the ranges shown in table 4.7. The results of this is shown in figures 4.9-4.11. As expected method 1 is more sensitive to atmospheric influence than method 2 and 3, since it do not compensate for it. The black area corresponds to very high temperature errors, showing that no method can make accurate measurement for low AM and PWV. However this is for a fixed absorber temperature and concentration factor of 600°C and 300, respectively. Hence this area will increase under less favorable conditions.

<table>
<thead>
<tr>
<th>Parameter ranges, sensitivity analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>AM</td>
</tr>
<tr>
<td>PWV</td>
</tr>
</tbody>
</table>

Table 4.7: Parameter range for values in sensitivity analysis batch

![Temperature error method 1](image)

Figure 4.9: Absolute error of Method 1, usually the error is negative.
Chapter 4. Results and Discussion

Figure 4.10: Method 2

Figure 4.11: Method 3
Chapter 5

Conclusion

In this work the simulation tool has been enhanced by coupling SMARTS to improve the simulation of the atmospheric transmittance. Further on a tool for batch simulation and post processing has been integrated to evaluate the result sensitivity with respect to atmospheric parameters and find limits to when solar blind measurements can be done. Gaussian models have been fitted to measured filter data to reduce computation time, although this was shown to have a negligible impact and was not used when doing the batch simulations.

When measuring the absorber temperature of a solar tower system, the atmospheric influence have shown to have a critical impact on the measurement accuracy. An optical depth below -3 is necessary for achieving solar blind conditions, which is a result of a humid atmosphere and/or high zenith angle. The absorber temperature has also proven to be a crucial parameter, since temperatures below 450°C yield no accurate measurements under any atmospheric conditions. Atmospheric temperature and aerosol depth have proven to be second order parameters that have a negligible impact on the measurement accuracy. Furthermore a low concentration factor is favorable since it leads to less reflected solar radiation from the tower onto the camera, even for a high absorbing coating, e.g. Pyromark 2500.

Since the meteorology data is not accessible in real time for any location, there will be an uncertainty in the precipitable water vapor. Further uncertainty is introduced in the estimation of the precipitable water vapor, which is not measured and has to be estimated. Without atmospheric compensation, the measurement accuracy has shown to be sensitive to this uncertainty, even under solar blind conditions. However if atmospheric compensation is used, the
results show to be less sensitive to this uncertainty, although this effect is only shown for measurements with an accuracy of more than 99 \%.

These results are obtained by running simulations of the temperature measurement concept, assuming negligible calibration errors. The results are on the one hand sensitive to accurate atmospheric simulations, where the external simulation tool SMARTS is used. Using other tools, such as MODTRAN, to simulate the atmospheric transmittance could yield very different results due to the spectral resolution of the atmospheric code and the narrow bandwidth of the atmospheric water absorption bands utilized to achieve solar blindness. On the other hand the influence of a noisy camera signal on the calibration curve would have to be accounted for in further simulations.

The batch simulation created in this work can be reconfigured to simulate scenarios at other locations and for further detectors and filters. As of now, the prototype used in the field does not use atmospheric compensation. Using the simulation tool, the compensation factor can be estimated based on available meteorology data, e.g. AERONET, and used in the calibration of the camera to improve measurement accuracy.
Bibliography


and M.V. Vilariño, “2018: Mitigation pathways compatible with 1.5°C in the context of sustainable development,” Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty, p. 51, 2021.


Appendix A

Derivation of analytical expression for temperature

Using Planck’s equation for black body radiation, it is possible to show that given the intensity for two different wavelengths, one can determine the temperature of a gray body under the influence of a gray atmosphere. The function for this is derived underneath:

Starting with Planck’s law for black body radiation, for a fixed wavelength $i$ and $j$.

\[
\text{Ratio} = \frac{\varepsilon \tau E_{\lambda_i}}{\varepsilon \tau E_{\lambda_j}} = \frac{E_{\lambda_i}}{E_{\lambda_j}} = \frac{\lambda_i^5 \varepsilon \tau}{\lambda_j^5 \varepsilon \tau} \frac{1}{e^{\frac{h c}{\lambda_i k_B T}} - 1} - 1 = \frac{\lambda_i^5 (e^{\frac{h c}{\lambda_i k_B T}} - 1)}{\lambda_j^5 (e^{\frac{h c}{\lambda_j k_B T}} - 1)} \approx \frac{\lambda_j^5 e^{\frac{h c}{\lambda_j k_B T}}}{\lambda_i^5 e^{\frac{h c}{\lambda_i k_B T}}} \quad (A.1)
\]

The approximation is validated since a temperature of $T \sim 600^\circ C$ and a wavelength of $\lambda \sim 10^{-6}$ nm corresponds to $e^{\frac{h c}{\lambda_j k_B T}} \approx e^{24} \approx 10^{11}$, thus it’s obvious that $10^{11} - 1 \approx 10^{11}$

Englin, 2022.
Appendix A. Derivation of analytical expression for temperature

\[ \frac{\lambda_j^5 e^{\frac{hc}{\lambda_j K_B T}}}{\lambda_i^5 e^{\frac{hc}{\lambda_i K_B T}}} \implies \ln \left( \frac{\lambda_j^5}{\lambda_i^5} e^{\frac{hc}{\lambda_j K_B T} - \frac{hc}{\lambda_i K_B T}} \right) = \ln \left( e^{\frac{hc}{\lambda_i K_B T} - \frac{hc}{\lambda_j K_B T}} \right) = \frac{hc}{(\lambda_i K_B T)} - \frac{hc}{(\lambda_j K_B T)} \]

\[ \ln \text{Ratio} + 5 \ln \lambda_i - 5 \ln \lambda_j = \frac{hc}{K_B T} \left( \frac{1}{\lambda_i} - \frac{1}{\lambda_j} \right) \implies \]

\[ T = \frac{hc}{K_B} \left( \frac{1}{\lambda_i} - \frac{1}{\lambda_j} \right) \left( \ln \text{Ratio} + 5(\ln \lambda_i - \ln \lambda_j) \right) \]  

(A.2)

Thus by calculating the ratio of the emitted radiation from two different wavelengths, one can determine the temperature of a gray body under atmospheric influence.
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