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On the Development of a Low Cost Pyrheliometer

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THE FLORIDA STATE UNIVERSITY
FAMU–FSU COLLEGE OF ENGINEERING

ON THE DEVELOPMENT OF A LOW COST PYRHELIOMETER

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ABSTRACT

This work presents the design and testing of a low cost pyrliometer ESC-MG-2 for direct normal irradiance measurements. A concentrating lens is used to focus the sunlight onto a small copper receiver disk. Four different focal lengths were tested to determine the best setup for highest accuracy. As a pyrliometer needs to follow the sun throughout the day to measure direct beam irradiance, a tracking system meeting the required accuracy was also designed and built. After preliminary results regarding the best focal length and tracking system were obtained, further testing was done with an improved design for the tracking system and the pyrliometer with the focal number F#2 and F#4. From the temperature difference between the receiver disk and the collimating tube surface, the incoming irradiance can be calculated. An Eppley Normal Incidence Pyrliometer (NIP) was used to calibrate and compare the irradiance measurements obtained with the ESC-MG-2. Integrating the irradiance measurements over the course of each test run yields the main interest of this work, the irradiation value. For the ESC-MG-2-F2 pyrliometer, thirteen test runs on very clear days, partly cloudy days and mostly cloudy days were done over the course of two months. The ESC-MG-2-F4 pyrliometer was tested under similar conditions in eight test runs. The accuracy of the ESC-MG-2-F2 and ESC-MG-2-F4 irradiation values is within $\pm 2\%$ and $\pm 1.5\%$, respectively. The standard deviation for the instantaneous irradiance measurement under steady state conditions is 2 W/m^2 for both instruments. The cost of the ESC-MG-2 pyrliometer prototype is estimated to be around \$1000. However, the cost can be reduced by a factor of two if mass produced in quantities of at least 50. Thus, the cost for the ESC-MG-2 pyrliometer, including the tracking system, is ten times lower than commercially available pyrliometers classified as field instruments.

CHAPTER 1

INTRODUCTION

1.1 Motivation

The most common instrument used for measuring solar radiation is the pyranometer, which measures global radiation. However, for concentrating solar applications, only the direct beam component of the radiation is necessary. Pyranometers can be modified in order to measure only the direct beam radiation but a simpler approach is to use a pyrhelimeter. Unlike pyranometers, for which low cost versions exist, commercially available pyrhelimeters suffer from the drawback of their high price, which is typically on the order of \$5000. As a result, most weather stations are equipped only with pyranometers from which pyrhelimeter data is derived. Depending on the weather, this derivation yields significant errors. Hence, an accurate, low cost pyrhelimeter is a necessity.

1.2 Types of Solar Radiation Instruments

The most crucial part of any solar radiation instrument is its radiation sensing device, also called detector. The following is a description of the four main types of solar radiation sensors: calorimetric, thermomechanical, thermoelectric and photoelectric detectors available[1]. This is followed by a brief overview of the three main types of solar radiation measurement instruments.

1.2.1 Solar radiation sensors

A calorimetric sensor is basically just a high conductive metal coated with a nonselective black paint to achieve a high absorptivity. The incoming irradiance causes a temperature change in the sensor, which can be measured using any of the following:

- A fluid cooled sensor measures the change in enthalpy by measuring the temperature difference of the fluid to calculate the solar radiation flux.
- The temperature of the metallic sensor can be measured directly. The temperature difference between the sensor and its surrounding is a linear function and independent of the ambient temperature[11].
- In a cavity type instrument, the temperature difference between an exposed and a shielded sensor is kept constant. This is achieved by supplying electrical heating to the shielded sensor. Thus, the insolation is proportional to the added electrical heating energy.

A thermomechanical sensor measures the radiation through a bending bimetallic plate. Two metals with different thermal expansion properties are attached to each other, only separated by a thermal insulation layer. One end is rigidly attached to the instrument with the other end able to move. The metal facing the sun is coated with a highly absorptive black paint whereas the other metal is coated with a reflective material. The bimetallic plate bends due to the different thermal expansion coefficient which results in a dislocation of the free movable end. This dislocation can be read mechanically or optically to determine the solar radiation flux.

A thermoelectric sensor is made of two different metallic wires which are directly connected to each other at both ends. If the two junctions are held at different temperatures, an electromotive force, also known as emf, is introduced. The emf depends on the materials used and is directly proportional to the temperature difference. Figure 1.1 shows different arrangements of thermoelectric sensors. A single thermoelectric sensor is called a thermocouple and is widely used. However, the main limitation of thermocouples is their accuracy as the emf for a single thermoelectric sensor is very small. For more precise measurements, the thermoelectric sensors can be connected in series to yield a higher potential difference. The resulting sensor is called a thermopile, which is typically used as a solar radiation sensor.

Most of the photoelectric sensors in solar instruments are photovoltaic devices made of mostly silicon based semiconducting materials. The electric current is a function of the incoming photon flux density from which the radiant flux can be determined. These devices

Figure 1.1: Various arrangements of thermoelectric sensors [1]

can be produced at low cost and they have a fast response time. However, a major drawback of silicon cells is their weak spectral response in the visible spectrum of sunlight as seen in Fig. 1.2.

Figure 1.2: Spectral response of a silicon cell in comparison to solar radiation spectrum[1]

1.2.2 Solar Radiation Instruments

Generally speaking, there are three main type of instruments for measuring solar radiation: the pyranometer, the pyranometer with a shading device and the pyrhelimeter.

Pyranometer

A pyranometer is designed to measure the total global irradiance, which is the direct normal radiation from the sun, the diffuse radiation from the entire sky dome and the reflected radiation from surrounding obstacles like snow covered mountains, buildings or, if tilted, from the ground. Figure 1.3 shows the schematic of a pyranometer. Note that the detector sees the entire sky dome. Figure 1.4(a) shows the setup for measuring direct and diffuse radiation from the entire sky dome whereas the setup shown in Fig. 1.4(b) measures direct, diffuse and reflected radiation. Most available pyranometer use silicon cells as a detector, whereas a state of the art pyranometer from Kipp & Zonen uses a thermopile as a detector.

Figure 1.3: Schematic of pyranometer[2]

Figure 1.4: Measuring global radiation on horizontal and inclined surfaces[2]

Pyranometer with shading device

A shading device can be added to a regular pyranometer to block the direct radiation from hitting the detector. This configuration measures the diffuse and reflected radiation only. Figure 1.5(a) shows the schematic of a shaded pyranometer and Fig. 1.5(b) shows a photograph of a shaded Kipp & Zonen pyranometer. The shadowing device is either a circular disk attached to an arm tracking the sun throughout the day or a thin shadowing

strip positioned at an angle (geographic latitude + solar declination) to the horizontal plane. Thus, the direct beam radiation can be determined by taking the measured values of a regular pyranometer (direct, diffuse, reflective) and subtracting the values obtained from a shaded pyranometer (diffuse, reflective). However, these values need to be corrected as a function of the incident angle of the sun rays on the detector.

(a) Setup for measuring diffuse radiation on horizontal plane by adding a shading devise

(b) Photograph of a shaded Kipp & Zonen pyranometer

Figure 1.5: Setup of pyranometer with shading strip for measuring diffuse radiation[2]

Pyrheliometer

A pyrheliometer, also referred to as an actinometer, measures direct normal radiation at normal incidence. To do so, the pyrheliometer needs to track the sun throughout the day. Two different approaches can be used to track the sun:

- Using the surface azimuth angle ψ and the zenith angle θ_z to track the sun with two axes throughout the day. An example of this strategy is the Kipp & Zonen actinometer[1].
- Eppley's Normal Incidence Pyrheliometer (NIP) allows the user to set the geographic latitude angle manually. The NIP only tracks the sun with one axis (the change of the hour angle, ω) and adjustment of the second axis (declination angle δ) is needed as often as required. The fastest rate of change for the solar declination is 0.4° per day at the vernal and autumnal equinox. Therefore, the adjustment of the solar declination angle can occur on a daily basis.

Figure 1.6: Schematic of the Eppley NIP[2]

Regardless of which approach is chosen, it is crucial to set up the instrument in a way that its basis is horizontal and that it faces exactly solar south at solar noon.

Figure 1.6 shows a schematic of the Eppley NIP. The sun's disk is approximately 0.5° when viewed from the Earth's surface. However, most standard pyrheliometers allow the measuring device to have a field of view of about 5° [12]. This is done to eliminate the need of a very precise, and therefore expensive tracking instrument. The drawback of this design is that not only the direct beam component of the solar radiation is measured but also the circumsolar component (see Fig. 2.1). However, the amount of circumsolar radiation is typically insignificant, except in conditions where there are a lot of aerosols in the air. Jeys and Vant-Hull [13] performed an experimental study on the effect of aperture angles on significant changes of beam radiation measurements. They showed that the circumsolar radiation on a day with thin uniform cloud cover becomes significant with up to 11% contribution.

1.3 History of Pyrheliometers

Pyrheliometers can be divided into standard (absolute), secondary standard and field instruments[14]. One of the earliest standard instruments was a water cooled pyrheliometer designed in the early 20th century by Abbot as described by Iqbal[1] and Duffie and Beckman[14]. A black cavity absorbs the incoming radiation and transfers it to the water. By measuring the water temperature at the inlet and outlet and controlling its flow rate, the intensity of the incoming radiation can be calculated. Figure 1.7 shows the schematic of the Abbot water flow pyrheliometer.

Figure 1.7: Abbot water flow Pyrheliometer[1]

An updated version of the Abbot pyrheliometer uses two identically water cooled chambers, but only one is exposed to the radiation. The second chamber is electrically heated so that the water temperatures leaving the chambers are identical. Hence, the electrical power

input is proportional to the incoming radiation. In fact, the thermocouples are connected differentially to each of the chambers, thus eliminating the need to measure the flow rate and the absolute temperatures. Unfortunately, both of the standard pyrhelimeters described above are not easy to operate. Similar to the Abbot standards, the Ångström electrical compensation pyrhelimeter is based on the calorimetric principle and is classified as a standard instrument. It uses two identical Manganin strips coated with black paint. Similar to the Abbot design, only one strip is exposed to the incoming radiation and the second one is heated electrically to reach the same temperature. The electrical power input is proportional to the incoming radiation after subtracting the losses. Due to the use of rectangular strips, the aperture of the Ångström pyrhelimeter is rectangular too, as can be seen in Fig. 1.8, which shows the Stockholm model of the Ångström electrical compensation pyrhelimeter.

Figure 1.8: Ångström Electrical Compensation Pyrhelimeter[1]

Figure 1.9: Abbot silver disk pyrheliometer[1]

Due to the difficulty of operation, Abbot constructed a portable silver disk pyrheliometer, as shown in Fig.1.9, that uses a thermometer immersed in mercury to measure the temperature of the silver disk. Diaphragms are used within the collimating tube to control the field of view. Rotatable polished metal shutters cut off the direct beam radiation in a controlled manner. The overall design is simple and mechanically solid. However, the Abbot silver disk pyrheliometer is unable to determine the irradiance from its principles, but needs to be calibrated against a standard pyrheliometer, thus making it a secondary standard pyrheliometer.

According to Iqbal[1] and Duffie and Beckman[14], the most common pyrheliometer used as a field instrument in the United States at present is the Eppley NIP as seen in Fig.1.10(a) , which measures the solar radiation with a wire-wound thermopile. The thermopile is coated with Parson's optical black. The collimating tube, which is filled with dry air and blackened on the inside, allows the thermopile to have a field of view of $5^{\circ}43'30''$. A crystal quartz window seals the sun facing end of the collimating tube to prevent wind gusts from entering the instrument.

(a) Eppley Normal Incidence Pyrheliometer (NIP) with one axis tracking model ST-1

(b) Kipp & Zonen Actinometer [1]

Figure 1.10: The most commonly found pyrheliometers in the US and in Europe

The most commonly found beam radiation measurement field instrument in Europe is the Kipp & Zonen actinometer shown in Figure 1.10(b), which uses a constantan-manganin

thermopile. Their newest field instrument pyrheliometer, the CHP-1 as seen in Fig. 1.11, uses a thermopile coated with black paint containing many micro-cavities to trap up to 97% of the incoming radiation. Its field of view is 5° and a quartz window, with transmittance in the range of 98% over the entire solar spectrum (280nm to 4000nm), guarantees a broad spectral absorption of solar radiation. The CHP-1 has a response time of less than 5 sec with an estimated error of 1% for daily integrated irradiation values. It is classified as a *First Class Normal Incidence Pyrheliometer* as defined by the World Meteorological Organization WMO[15].

Figure 1.11: Kipp & Zonen Pyrheliometer CHP-1 [3]

In 1983, Hsieh and Wang [4] presented a paper about a highly accurate copper disk pyrheliometer. They operated a shutter to block the sunlight periodically from heating the sensor. Looking at the heating and cooling rate of the sensor when they are at the same temperature as seen in Fig.1.12(b) allowed them to determine the solar irradiance. The biggest advantage of this method is that it is totally independent of the heat transfer coefficient in the measurement as they cancel each other out. The apparatus was tested in the lab and in the field and yielded an uncertainty of $\pm 0.61\%$ compared with an Eppley Normal Incidence Pyrheliometer (NIP). However, as the collimating tube is open to the environment, strong wind gusts may enter the instrument and affect its stability. A schematic of this copper disk pyrheliometer is shown in Fig.1.12(a).

(a) Schematic of Copper Disk Pyrheliometer

(b) Heating and cooling curve used to determine the slope at identical temperatures, from which the solar irradiance can be computed

Figure 1.12: Copper disk high precision pyrheliometer designed by Hsieh and Wang[4]

Dayan et al.[11] presented a copper disk pyrheliometer in 2004, using a convex lens to focus the incoming radiation onto a small receiver disk, thus increasing the temperature of the receiver. Using a small disk allowed for the measurement of the temperature of the receiver with a single thermocouple rather than a thermopile. An analytical model was developed to determine the optical efficiency of the instrument and the effective heat transfer coefficient using transient measurements. Incorporating this into a single constant, the irradiance can be simply calculated from the temperature difference of the receiver and the ambient. The time response is about 140 seconds which allows about 2 minutes of steady state measurement with the design given, as measurements are done stationary. This inexpensive pyrheliometer is simple, portable and can be used for instantaneous field measurements.

CHAPTER 2

FUNDAMENTALS OF SOLAR RADIATION

Solar energy can be divided into primary and secondary solar resources. Solar radiation is considered to be a primary solar resource whereas wind, wave power, and biomass, which are created by the sun indirectly due to density gradients or photosynthesis, are secondary solar resources. The focus of this work lies in the primary solar resource of radiation.

2.1 Application Considerations

Taking a closer look at solar radiation, it is crucial to differentiate between direct, diffuse and reflected radiation. Figure 2.1 shows the different forms of radiation. Depending on the solar application, only a certain part of the radiation can be used. Table 2.1 shows the useful radiation components for various solar applications in tabular form.

Table 2.1: Useful radiation components for different solar applications

Solar application	Useful radiation components
Photovoltaic	Beam, diffuse and reflected
Flat plate collector	Beam, (diffuse and reflected)
Concentrating Solar Power CSP	Beam only

Devices to measure the different radiation parts are commercially available. As mentioned in Section 1.2.2, a pyrliometer measures the direct beam radiation, and a pyranometer measures the total radiation. If shaded from the beam radiation, a pyranometer measures the diffuse and reflected radiation. Even though these devices are commercially available, the drawback of a pyrliometer in particular is its price. As of now, a state of the art

Figure 2.1: Beam, diffuse and reflected radiation

pyrheliometer costs at least \$2500, plus an additional \$2500 for the tracking system. Hence, the objective of this work is to design, build, and test a low cost pyrheliometer with tracking system that will cost \$500 when mass produced.

2.2 Sun and Earth's Atmosphere

The sun is a sphere with a diameter of about $1.39 \times 10^9 \text{m}$. It consists of extremely hot and condensed gaseous matter with a surface temperature of 5777 K [14]. The distance between the sun and the earth varies between $1.47 \times 10^{11} \text{m}$ and $1.52 \times 10^{11} \text{m}$. The average distance is $1.495 \times 10^{11} \text{m}$, which is defined as one astronomical unit (1 AU). The maximum distance

from the sun ($\sim$ July 3rd) is called the aphelion whereas the minimum earth-sun distance is called perihelion ($\sim$ January 2nd). Figure 2.2 shows the different locations of the earth on its orbit throughout the year.

Figure 2.2: Variation in earth-sun distance and their generic terms for the northern hemisphere

2.2.1 Solar spectrum

The surface temperature of the sun of 5777 K was actually derived from comparing the amount of energy radiating from a perfect emitting blackbody. The Stephan-Boltzmann law of radiation states that the amount of radiation leaving a body is proportional to the fourth power of its temperature and it is written as

$$E = \sigma T^4 \quad (2.1)$$

where $\sigma = 5.67 \times 10^{-8} \text{ W/m}^2$ and the measured temperature, T , is in Kelvin. In general, good emitters of radiation are also good absorbers of radiation in a certain frequency range. Bodies which absorb and emit radiation almost perfectly are called black bodies, which include the Earth and sun. Figure 2.3 shows the two curves for the actual blackbody spectrum for $T = 5777 \text{ K}$ and for the measured extraterrestrial irradiance. Commonly, the solar irradiance spectrum is divided into ultraviolet ($< 400 \text{ nm}$), visible ($400\text{-}800 \text{ nm}$), and infrared ($> 800 \text{ nm}$) ranges.

Figure 2.3: Comparison of a blackbody radiation versus the extraterrestrial solar radiation[5]

Plank's law describes the spectral radiation power of a blackbody as a function of not only its temperature, but of the wavelength as well and it is defined as

$$I(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda kT}} - 1} \quad (2.2)$$

where h is Planck's constant (6.626×10^{-34} J-s), λ is the wavelength in meters, c is the speed of light in m/s, k is the Boltzmann constant of $1.3806504 \times 10^{-23}$ in J/K (not to be confused with the Stephan-Boltzmann constant) and T is the body temperature in Kelvin. The unit of the spectral radiation is $\text{W}/(\text{m}^2\text{sr m})$ where sr is the abbreviation of steradians, which is the SI unit for a solid angle (dimensionless). It is suggested to neglect the unit steradians in scientific text as there is no physical meaning behind it.

In addition, Wien's law describes exactly the wavelength of maximum emission. It is inversely proportional to the body temperature in Kelvin, with b being a constant of 2897.

$$\lambda_{max} = \frac{b}{T} \quad (2.3)$$

The wavelength of maximum emission of a cooler body like the Earth is much larger than that of the sun. Figure 2.4 shows the shift of the emissivity curve of a cooler body to the right. Note that the "Spectral Intensity" axis is not drawn to scale.

Figure 2.4: Comparison of the wavelength of maximum emission of the sun and of the Earth [6]

2.2.2 Spectral scattering and absorptance

Certain wavelengths of the extraterrestrial radiation are scattered or absorbed while passing through the Earth's atmosphere. Lord Rayleigh derived a theory in the 19th century to describe the scattering of direct solar radiation. In his honour, it was named Rayleigh scattering [1]. In general, it can be said that shorter wavelengths scatter more easily than longer and therefore, scattering is a function of the wavelength, λ . Based on Rayleigh's theory, it can be easily explained why the sky looks blue during sunny days and why sunset and sunrise are red. Gases in the atmosphere scatter shorter (blue) wavelengths more easily than longer (red) wavelengths. At sunrise and sunset, the airmass is much higher than during the day which means that the sunlight passes through more atmosphere. Therefore, much of the blue light has been scattered out by the time it reaches our eyes, leaving only the long-wave red/yellow light behind.

On the other hand, spectral absorptance of solar radiation by gases is a selective process rather than a function of the wavelength observed in scattering. The major absorber among the dry air molecules are CO₂, O₃, N₂O, CO, O₂, CH₄, and N₂ [1]. Figure 2.5 shows the extraterrestrial solar irradiance and the solar radiation at sea level with the impact of spectral scattering and absorption. In Figure 2.6, it can be seen that due to the ozone and Rayleigh scattering, most of the UV radiation ($\lambda \leq 400$ nm) is blocked from reaching the Earth's surface. On the other hand, water vapor absorbs almost 100% of the long-wave infrared radiation, which is also known as the greenhouse effect. Without this absorption, the Earth's average surface temperature would be 255 K instead of 287 K [16].

Figure 2.5: Spectral radiation absorptance of various gases[7]

Figure 2.6: Spectral absorptance of various gases[8]

2.3 Sun-Earth angles

The position of the Earth with respect to the sun can be described by three different angles. Figure 2.7 shows the solar declination angle δ , the hour angle ω , and the geographic latitude angle ϕ . The following subsections discuss the importance and derivation of each angle as well as the measurement of time.

Figure 2.7: Sun-Earth angles

2.3.1 Time

The Earth's surface is divided into different time zones. The standard time zone meridians run every 15° from north to south, based on the fact that the earth rotates once around its axis in 24 hours ($15^\circ/\text{hour}$). The 0° meridian passes through Greenwich in England and both poles. This reference meridian is also known as the Prime Meridian[12] and it is also the location where Universal Time is measured (previously known as Greenwich Mean Time GMT). Locations east of Greenwich are indicated with a capital E next to the longitude

degree value whereas locations west of Greenwich use a capital W. For example, 63°E or 84°W indicate locations which are 63°east or 84°west of the Prime Meridian, respectively. However, standard time can not be used to predict the direction of the incoming radiation with respect to a certain location. Instead, *solar time* was introduced, and it depends on the angular motion of the sun across the sky. Solar noon, which occurs when the sun is exactly due south, is used as the reference. Solar time only depends on longitude, not latitude. The relationship between solar time and standard time is described by equation 2.4

$$\text{Solar time} = \text{Standard time} + 4(L_{st} - L_{loc}) + E \quad (2.4)$$

with L_{st} being the standard meridian for the local time zone, L_{loc} being the longitude of the location and E being the the equation of time in minutes. The second term corrects for the difference in longitude between the standard local meridian of the location and its actual longitude. The standard local meridian can easily be found by multiplying the time difference between the standard local time and the Universal Time by 15. For example, Tallahassee, FL is located in the Eastern Time Zone, which is five hours behind Universal Time. Therefore, the standard meridian for Tallahassee is $5 \times 15^\circ = 75^\circ$.

The equation of time, E , takes the perturbation of the Earth's rate of rotation around its axis into account. These perturbations[17] are due to:

- The fact that the Earth travels on an elliptical rather than a circular path around the sun. Thus, the Earth travels faster when it is nearer the sun than when it is farther away.
- The Earth's axis is tilted with respect to the ecliptic plane.
- The Earth rotates at an irregular rate around its axis.
- The Earth "wobbles" on its axis due to the rotation around the center of gravity of the earth and the moon together.

The equation of time found in the literature [1][18] can be written as

$$\begin{aligned} E = & 229.2(0.000075 + 0.001868 \cos B - 0.032077 \sin B \\ & - 0.014615 \cos 2B - 0.04089 \sin 2B) \end{aligned} \quad (2.5)$$

where B can be found from

$$B = (n - 1) \frac{360}{365} \quad (2.6)$$

with n being the n^{th} day of the year. Equation 2.5 uses degrees, not radians. Figure 2.8 shows the difference between solar time and local time, including the daylight saving shift which usually occurs around the end of March and the end of October, depending on the location.

Figure 2.8: Difference between solar time and local time (including daylight saving time shift)

2.3.2 Declination angle δ

The Earth rotates around the sun on a plane called the ecliptic plane[1]. In addition, the Earth rotates around its own axis which points towards the star Polaris with an error of

only about 45 min of an arc (13 mrad)[12]. This axis is 23.45° inclined with respect to the ecliptic plane. The angular difference between the Earth's axis and the normal to the ecliptic plane remains constant. Thus, the angle between the ecliptic plane and the Earth's equatorial plane stays constant too. Nevertheless, the angle between the Earth-sun line and the Earth's equatorial plane, which is called the solar declination δ , changes throughout the year between -23.45° and 23.45° . Figure 2.9 shows the position of the Earth at the summer solstice. Its value is positive if the Earth's north pole points towards the sun and negative if it points away from the sun. Hence, for the northern hemisphere, the declination angle is negative in the winter and positive in the summer whereas in the southern hemisphere, the declination angle takes positive values in the winter and negative values in the summer. The variation of the declination angle is what causes the seasonal change in temperature.

Figure 2.9: The earth shown in the position of the summer solstice[9]

For most engineering purposes, it is accurate enough to use the following approximation

Figure 2.10: Variation of the declination angle throughout the year

formula suggested by Cooper[19] in 1969:

$$\delta = 23.45 \sin \left(360 \frac{284 + n}{365} \right) \quad (2.7)$$

The following is a more accurate but much more complicated equation proposed by Spencer[18] in 1971, which can be used for computational purposes.

$$\begin{aligned} \delta = & (180/\pi) (0.006918 - 0.399912 \cos B + 0.070257 \sin B \\ & - 0.006758 \cos 2B + 0.000907 \sin 2B \\ & - 0.002697 \cos 3B + 0.00148 \sin 3B \end{aligned} \quad (2.8)$$

The error of the more accurate equation is less than 0.035° [14]. The absolute error between the approximation of Cooper and the more accurate equation of Spencer can be seen in Figure 2.10 and is maximally 1.4° . The fastest change in the declination angle is 0.4° per day at the vernal and autumnal equinox.

2.3.3 Hour angle ω

The hour angle ω is defined as the angle between the meridian on which the observer is located and the meridian parallel to the sun rays (see Figures 2.7 and 2.11). Note that the sign convention for the hour angle ω is as follows: east of south yields negative values, south is zero, and west of south yields positive values. The hour angle is based on the 24 hour rotation of the earth around its axis. Therefore, it can be simply said that the hour angle changes 15° each hour or 1° every 4 minutes. Mathematically, it can be written as

$$\omega = 15^\circ(\text{Solar time in hrs} - 12) \quad (2.9)$$

The sunrise and sunset hour angles are of special interest. They can be found from the following equation.

$$\omega_s = \cos^{-1} \left[-\frac{\sin\phi \sin\delta}{\cos\phi \cos\delta} \right] = \cos^{-1}(-\tan\phi \tan\delta) \quad (2.10)$$

As previously discussed, the sunrise hour angle has a negative value whereas the sunset hour angle is positive. In addition, the number of sunshine hours can be calculated from the sunrise hour angle as

$$N = \frac{2 \omega_s}{15^\circ/\text{hr}} \quad (2.11)$$

or by using the sun-earth angles

$$N = \frac{2}{15} \cos^{-1}(-\tan\phi \tan\delta) \quad (2.12)$$

2.3.4 Geographic latitude ϕ

The geographic latitude ϕ describes the angle between the equatorial plane and the line of an arbitrary point on the Earth's surface to the center of the Earth. The angle range is from 0 to 90 degrees and the sign convention is positive for the northern hemisphere and negative for the southern hemisphere.

2.4 Observer angles

The position of the sun with reference to a horizontal plane can be described at any time during the day by two angles, the zenith angle θ_z and the solar azimuth angle ψ . A visual description of useful angles can be seen in Figure 2.11. Note that the sign convention for the solar azimuth angle ψ is the same as that of the hour angle ω .

Figure 2.11: Sun-observer angles

2.4.1 Zenith angle θ_z

The zenith angle θ_z is the angle between the line normal to the horizontal plane of the observer and the line from the observer to the center of the sun. A trigonometric relation between the zenith angle θ_z and the sun-Earth angles can be written as

$$\cos \theta_z = \sin \delta \sin \phi + \cos \delta \cos \phi \cos \omega \quad (2.13)$$

with θ_z taking values between 0° and 90° for sunrise/sunset and solar noon, respectively. The solar altitude, also known as solar height or solar elevation is the complement of the zenith angle θ_z to 90° .

$$\alpha = 90^\circ - \theta_z \quad (2.14)$$

2.4.2 Solar azimuth angle ψ

The solar azimuth angle ψ is measured between the line from the observer to the center of the sun projected to the horizontal plane and a line that runs south in the northern hemisphere and north in the southern hemisphere.

$$\cos \psi = \frac{(\sin \alpha \sin \phi - \sin \delta)}{\cos \alpha \cos \phi} \quad (2.15)$$

With the knowledge of the sun-Earth angles, the observer angles and the solar time, the position of the sun with respect to a horizontal, south-facing observer can be calculated for any given time. This is important as the pyrheliometer needs to be pointed directly at the sun at all times to measure direct beam radiation.

CHAPTER 3

DESIGN CONSIDERATIONS FOR THE PYRHELIOMETER

In this chapter, the optical as well as the mechanical design considerations are described. An analysis of the heat transfer from the copper receiver disk was done to predict the maximum temperature and the response time of the system.

3.1 Pyrheliometer Aperture Angle

Taking only the sun disk into account, the aperture angle on the Earth's surface can be calculated as

$$\begin{aligned}\alpha &= \arctan \frac{\text{Radius sun}}{\text{Distance Sun-Earth}} \\ &= \arctan \frac{1'391'960 \text{ km}}{1.496 \times 10^8 \text{ km}} = 0.533^\circ\end{aligned}\tag{3.1}$$

However, all pyrheliometers are designed with a bigger aperture angle as it is impractical to build such a precisely tracking device. Hence, a pyrheliometer measures not only the direct beam radiation but also a certain amount of circumsolar radiation. Under clear sky conditions, the radiation from the aureole is negligible. Figure 3.1 shows the rapid decrease in radiance outside the solar disk angle of 0.53° or 4.8 mrad . However, on a hazy day with thin uniform clouds, the circumsolar radiation contributes up to 11% to the measured irradiance [13].

Figure 3.1: Circumsolar radiation intensity[10]

Iqbal [1] lists the different aperture angles (degrees of field of view) of the most common pyrheliometers. These values are summarized in table 3.1.

Table 3.1: Aperture angles of popular pyrheliometers

Pyrheliometer	PACRAD PMO ACR	Abbot silver- disk	Ångström electrical compensation	Linke- Fuessner Kipp & Zonen	Eppely NIP
Opening angle ξ_0	Circular 5°	Circular 6°	Rectangular 5° × 10°	Circular 10°12'	Circular 5°43' 30"

Figure 3.2: Field of view angles for pyrheliometers

Figure 3.2 shows a schematic of a collimating tube with its receiver radius r , its transparent radius R , the opening half angle ξ_0 , the limit angle ξ_1 , and the slope angle ξ_2 . The parameters can be normalized to make them independent of the actual dimension by defining two new parameters:

$$a = \frac{R}{r}$$

$$b = \frac{L}{r}$$

With these two new parameters, the three angles ξ_0 , ξ_1 , and ξ_2 can be described as follow:

$$\begin{aligned}\xi_0 &= \tan^{-1} \left(\frac{a}{b} \right) \\ \xi_1 &= \tan^{-1} \left(\frac{a+1}{b} \right) \\ \xi_2 &= \tan^{-1} \left(\frac{a-1}{b} \right)\end{aligned}$$

As recommended by the WMO [15], the slope angle ξ_2 should be between 1° and 2° and the ratio of collimating tube length to the radius of the receiver, b , has to be bigger than 15. Given these two boundaries, it yields that the opening half angle ξ_0 has to be smaller than 4°. The WMO suggests that all new pyrheliometers are designed with an opening half angle of 2.5°. Thus, the opening angle chosen for the ESC-MG-2 pyrheliometer designed at ESC has an opening half angle of 2.5°.

3.2 Pyrheliometer optics

A molded acrylic aspheric lens from Edmund Optics was chosen to focus collimated sun rays onto the copper receiver disk. The size of the receiver disk is a function of the focal length and the angle of acceptance. As the focal length can be measured physically, the back focal length (BFL) is introduced, which describes the distance from the back of the lens to the focal point. As mentioned in Section 3.1, the maximum angle of acceptance ξ_0 is 4°. In this work, the angle of acceptance was chosen to be $\pm 2.5^\circ$. Figure 3.3 shows an approximate derivation of the receiver plate size.

$$\alpha = \arctan \left(\frac{d}{2 \text{ BFL}} \right)$$

with a being

$$a = \frac{\text{BFL}}{\cos \alpha}$$

and b being

Figure 3.3: Effect of error in incoming radiation

$$b = a \tan \xi_0 = \frac{\text{BFL}}{\cos \alpha} \tan \xi_0$$

Considering that ξ_0 is only 2.5° , the angle β is simply assumed to be 90° . Knowing a and b , the radius r of our receiver disk can be calculated as,

$$\begin{aligned} r &= \frac{b}{\cos \alpha} = \frac{\tan \xi_0}{\cos^2 \alpha} \text{BFL} \\ &= \frac{\tan \xi_0}{\cos^2 \left(\arctan \frac{d}{2 \text{BFL}} \right)} \text{BFL} \end{aligned}$$

A comparison of the approximate receiver disk size with a more precise optical calculation was done. Therefore, Snell's law, more commonly known as the law of refraction, as described in Eq.3.2 was used. Figure 3.4 describes the Snell's law visually.

$$\frac{\sin \theta_1}{\sin \theta_2} = \frac{v_1}{v_2} = \frac{n_2}{n_1} = \frac{1.49}{1} \quad (3.2)$$

Figure 3.4: Snell's Law or Law of Refraction

A Matlab routine was written to calculate the lines perpendicular to the aspheric shape. By considering the acceptance angle of $\pm 2.5^\circ$ and the angles θ_2 , θ_3 , θ_4 it was possible to calculate the size of the receiver disk. Figure 3.5 shows the graphical determination of the disk size for an acceptance angle of $\pm 2.5^\circ$ and a focal number F#2. The results for all of the lenses tested are shown in table 3.2.

Figure 3.5: Example of disk size determination with MATLAB routine

Table 3.2: Receiver disk diameter for various lens

Acrylic aspheric lenses	F#8	F#6	F#4	F#2
Back Focal Length (BFL)	199 mm	148 mm	97.2 mm	45.8 mm
Transparent diameter	23.9 mm	23.9 mm	23.9 mm	23.9 mm
Receiver disk diameter approx.	17.4 mm	13 mm	8.55 mm	4.13 mm
Receiver disk diameter exact	18 mm	13.6 mm	9.4 mm	5.4 mm

3.3 Heat transfer

Having determined a disk size, it is appropriate to consider an energy balance on the receiver disk, as seen in Fig. 3.6. The first law of thermodynamics for this closed system states

$$\frac{dE}{dt} = \dot{Q}_{sun} - \dot{Q}_{radiation} - \dot{Q}_{convection} - \dot{Q}_{conduction} \quad (3.3)$$

which simplifies for steady state to

$$\dot{Q}_{sun} = \dot{Q}_{radiation} + \dot{Q}_{convection} + \dot{Q}_{conduction} \quad (3.4)$$

Figure 3.6: Copper receiver plate inside the pyrhelimeter

The radiation loss is a function of the area of the receiver plate A_r , its emissivity ε , the

Boltzmann constant σ , and is highly dependent on the absolute temperature of the receiver in Kelvin.

$$\dot{Q}_{radiation} = A_r \varepsilon \sigma (T_c^4 - T_\infty^4) \quad (3.5)$$

The convection loss is a function of the area of the receiver plate A_r , the average heat transfer coefficient of all the surfaces $h_{average}$, and the temperature of the receiver.

$$\dot{Q}_{convection} = A_r h_{average} (T_r - T_\infty) \quad (3.6)$$

The conduction losses through the thermocouple wires can be described as

$$\dot{Q}_{conduction} = -k_{tc} A_{tc} \frac{\partial T_{tc}}{\partial z} \quad (3.7)$$

with the transient conduction equation for the thermocouple as

$$\frac{\partial^2 T_{tc}}{\partial z^2} = \frac{1}{\alpha_d} \frac{\partial T_{tc}}{\partial t} \quad (3.8)$$

where α_d denotes the thermal diffusivity of the thermocouple wire material. Plugging Equations 3.5 - 3.7 into Equation 3.3 yields

$$\frac{dE}{dt} = m_r c_p \frac{dT_r}{dt} = I_b A_l \alpha \eta_{opt} - A_r \varepsilon \sigma (T_r^4 - T_\infty^4) - A_r h_{average} (T_r - T_\infty) + k_{tc} A_{tc} \frac{\partial T_{tc}}{\partial z} \quad (3.9)$$

where I_b is the direct beam irradiance, A_l the transparent area of the lens, η_{opt} the optical efficiency of the lens and α being the absorptivity of the receiver disk. The radiation and convection terms can then be combined into a single term by introducing the effective heat transfer coefficient h_{eff} as described by Dayan et al.[11]. Equation 3.9 simplifies to

$$m_r c_p \frac{dT_r}{dt} = I_b A_l \alpha \eta_{opt} - A_r h_{eff} (T_r - T_\infty) + k_{tc} A_{tc} \frac{\partial T_{tc}}{\partial z} \quad (3.10)$$

Applying the Laplace transformation on this equation yields two distinct solutions as shown

by Dayan et al.[11]. The simpler one considers the limiting condition with no thermal conductance into the thermocouple. Equation 3.11 is the well known solution of a lumped capacity system with θ_r being the temperature difference between the receiver and the collimating tube.

$$\theta_r(t) = \frac{\alpha\eta_{opt}I_bA_l}{h_{eff}A_r} \left(1 - e^{-\frac{h_{eff}A_r}{m_rc_p}t} \right) \quad (3.11)$$

$$T(t) = T_\infty + \frac{\alpha\eta_{opt}I_bA_l}{h_{eff}A_r} \left(1 - e^{-\frac{h_{eff}A_r}{m_rc_p}t} \right) \quad (3.12)$$

The more complicated solution includes the thermocouple cooling effect. For a simpler presentation, we define

$$a = \frac{h_{eff}A_r}{m_rc_p}, \quad b = \frac{\alpha\eta_{opt}I_bA_l}{m_rc_p}, \quad d = \frac{k_{tc}A_{tc}}{\sqrt{\alpha}m_rc_p}$$

where A_{tc} is the effective area calculated by using the cross-sectional area of one wire A_w (both wires have the same diameter) and the weighted average of the wire's thermal diffusivity as described by Dayan et al. [11].

$$A_{tc} = A_w \left(1 + \sqrt{\frac{\alpha_{d2}}{\alpha_{d1}}} \right) \quad (3.13)$$

$$\theta_r(t) = \frac{b}{a} \left[\frac{\lambda_1[\text{erfc}(\lambda_2\sqrt{t})e^{\lambda_2^2t} - 1] - \lambda_2[\text{erfc}(\lambda_1\sqrt{t})e^{\lambda_1^2t} - 1]}{\lambda_2 - \lambda_1} \right] \quad (3.14)$$

with λ_1 and λ_2 being the eigenvalues defined as

$$\lambda_1 = \frac{d}{2} - \frac{\sqrt{d^2 - 4a}}{2} \quad \lambda_2 = \frac{d}{2} + \frac{\sqrt{d^2 - 4a}}{2}$$

In our case, Equation 3.14 can not be used because λ_1 and λ_2 appear as complex conjugates.

A Taylor Series expansion can be used to find the solution if we define

$$\lambda_{1,2}\sqrt{t} = x \pm iy$$

and expand the complementary error function as follow.

$$\begin{aligned} \operatorname{erfc}(\lambda\sqrt{t}) &= \operatorname{erfc}(x \pm iy) = 1 - \operatorname{erf}(x \pm iy) \\ &= 1 - \frac{2}{\sqrt{\pi}} \sum_{n=0}^{\infty} \frac{(-1)^n (x \pm iy)^{2n+1}}{(2n+1)n!} \end{aligned} \quad (3.15)$$

For simplification, let the Taylor series expansion of $\operatorname{erfc}(\lambda_1\sqrt{t})$ be D_1 and for $\operatorname{erfc}(\lambda_2\sqrt{t})$ be D_2 . Implementing these definitions into equation 3.14 yields the thermal response for complex eigenvalues as

$$\theta_r(t) = \frac{b}{a} \left[\frac{\lambda_1[D_2 e^{\lambda_2^2 t} - 1] - \lambda_2[D_1 e^{\lambda_1^2 t} - 1]}{\lambda_2 - \lambda_1} \right] \quad (3.16)$$

which was solved using a Matlab code. Figure 3.7 shows the transient response for the F#4 pyrheliometer. It includes the lumped capacity model, the thermocouple cooling effect model and experimental data. It can be seen that the thermal response time is about 150 seconds for the experimental data. At that time, the difference between the lumped capacity model and the thermocouple (TC) cooling effect model is about 4-5°C. Eventually, the TC cooling effect model reaches the same steady state temperature as the lumped capacity model. The experimental data fits the lumped capacity model better than the TC cooling effect model especially because the temperature values of the experimental data remain constant after about 150 seconds. In the following chapters of this work, the energy balance is done without considering the conduction loss into the thermocouple wires as there is negligible effect. Furthermore, we are mainly interested in the integrated irradiation value rather than the instantaneous measurements.

Figure 3.7: Transient cooling and heating for lumped capacity model, TC cooling effect model and experimental data for F#4

CHAPTER 4

EXPERIMENTAL SETUP

Measurements of instantaneous irradiance were done using the ESC-MG-2 pyrheliometer and Eppley NIP. Integrating the irradiance over the course of the test run yields the main interest of the measurements, the irradiation. The NIP was used as a reference instrument to calibrate the ESC-MG-2. It was also used to compare with the subsequent results that were obtained. Experiments were performed inside the solar park located next to the Energy & Sustainability Center (ESC) on the FSU main campus. Figure 4.1 shows the setup of the experiment performed with the ESC-MG-2 pyrheliometer on the left side and an Eppley NIP on the right side.

Figure 4.1: Experimental Setup inside the solar park on the FSU main campus

The solar park is surrounded by tall buildings, which did not allow for the acquisition of measurements at high zenith angles ($\theta_z > 70^\circ$). For that reason, a second series of experiments were performed on top of the Meteorology building with an unobstructed view. Hence, measurements of direct beam radiation were obtained from sunrise until sunset. Figure 4.2 shows the experimental setup on top of the Meteorology building.

Figure 4.2: Experimental Setup on the roof of the meteorology building

The experimental setup consists of three main components: the pyrheliometer itself, the tracking system and the data acquisition. The following sections explain the details of the main components.

4.1 Pyrheliometer

The main components of the ESC-MG-2 prototype pyrheliometer are the collimating tube, the receiver disk, which was soldered to a bare wire thermocouple, and the concentrating lens. An exploded view of the ESC-MG-2 pyrheliometer can be seen in Fig. 4.3. The following is a brief description of each of the main components.

Figure 4.3: Exploded view of the ESC-MG-2 pyrheliometer

4.1.1 Collimating Tube

The collimating tube is made of a standard, thin walled aluminium tube. The inside is black anodized to minimize the reflectivity and a thermocouple is mounted to the inner surface to measure its temperature, as seen in Fig. 4.4. The preliminary design had four different lengths for the collimating tubes to investigate the influence of four different focal lengths on the temperature distribution inside the collimating tube. All of the other parts, apart from the size of the receiver disk, were the same.

Figure 4.4: Collimating tube with the interior black anodized. A surface mounted thermocouple measures the temperature of the wall

4.1.2 Receiver Disk

The receiver disk itself is made of a 0.5 mm thick circular copper disk. The temperature of the receiver disk is measured using a single bare wire K-type thermocouple of the type BARE-24-K-12 from Omega Engineering. The thermocouple bead was carefully soldered to the center of the disk. To ensure an isothermal temperature distribution throughout the disk, numerical calculations of the heat transfer from the disk were performed using a Matlab routine. The temperature difference between the edge and the center of the disk is 0.15°C and 0.2°C for the receiver disk using the lens with focal number 2 and 4, respectively.

Table 4.1 gives an overview of the temperature difference from the edge to the center of the receiver disk for three different thicknesses. It can be seen that the temperature difference decreases significantly if the thickness is increased from 0.1 mm to 0.5 mm. However, if the thickness is increased even further, the temperature difference decrease is not as significant. Therefore, the thickness for the receiver disk was chosen to be 0.5 mm. Figure 4.5 shows the copper receiver disk, which is coated in black paint, soldered to a bare wire thermocouple.

Table 4.1: Temperature difference within the receiver disk for various thickness

Thickness of disk	F#2	F#4	F#6	F#8
0.1 mm	0.75°C	1.0°C	1.50°C	2.0°C
0.5 mm	0.15°C	0.2°C	0.30°C	0.4°C
1 mm	0.10°C	0.1°C	0.15°C	0.2°C

Figure 4.5: Temperature measurement of the receiver disk and air inside the pyrheliometer

A two hole round ceramic insulator is used to hold the receiver disk in position and to insulate the chromel wire from the alumel wire. For measuring the air temperature inside the collimating tube, an exposed thermocouple of the type 5TC-TT-K-24-36 from Omega Engineering is used. To compare the temperature of the air with the temperature of the collimating tube, a surface thermocouple of the type SA1-K from Omega Engineering is adhered to the collimating tube's inner surface, as shown in Fig. 4.4.

4.1.3 Concentrating Lens

The use of a concentrating lens guarantees accurate results, even with less than precise tracking systems since the incoming radiation is focussed onto a small area of the receiver disc. The concentrating lens is of aspheric shape and made of acrylic glass. The benefit of an aspheric shaped lens is its very small spot size compared to a regular planoconvex lens. Figure 4.6 shows the two molded acrylic aspheric lens used, which were purchased from Edmund Optics. The NT48-183/NT48-184 are lenses with the focal number F#2 and F#4, with a corresponding back focal length of 45.8 mm and 97.2 mm , respectively.

(a) F#2

(b) F#4

(c) F#2 Side view

(d) F#4 Side view

Figure 4.6: Molded Acrylic Aspheric Lens

In addition, the lens contains an anti-reflective coating to reduce the reflectivity to less than 0.5% in the visual (VIS) radiation range from 450 to 650 nm. However, acrylic

glass blocks ultraviolet radiation completely and due to the coating, the transmittance for wavelengths higher than 650 nm decreases rapidly. Figure 4.7 shows the low reflectance of the VIS coating in the range of 400 nm to 700 nm and the rapid increase of the reflectance for wavelengths higher than 700 nm. Due to this high reflectance of wavelength outside the visual spectrum, only part of the solar radiation actually transmits through the lens onto the receiver disk.

Figure 4.7: Wavelength dependent reflectivity of the VIS coated lens compared with total solar spectrum

Integrating the spectral irradiance between 350 nm and 800 nm and comparing it to the total integrated irradiance results in a maximum optical efficiency of the VIS coated acrylic lens of about 58%. For a higher optical efficiency, an uncoated lens or a coating specifically for the visible and near-infrared wavelength range should be chosen. Figure 4.8

shows the wavelength depending transmittance of solar radiation through an uncoated acrylic lens. Integrating the spectral irradiance between 350 nm and 1130 nm at a transmittance of 90% results in an increased optical efficiency of about 72%. Appendix A contains more information about properties of the lens used and various coatings.

Figure 4.8: Wavelength depending transmittance of acrylic lens

4.1.4 Alignment Control

A small alignment hole in the lens holder cover allows the sun rays to pass through and a center bore in the tube bottom attachment is used for alignment. If perfectly aligned, the sun rays shining through the alignment leave a sun spot that is lined up with the center of the center bore. Figure 4.9 shows the pyrheliometer directly facing the sun and it can be seen that the sun spot is slightly off-center. If the focussed sun spot does not hit the receiver

disk anymore, the temperature of the receiver disk drops instantly rather than gradually, as is typically observed with the use of a non-concentrating lens, such as that in the Eppley NIP. This is a big advantage of using a concentrating lens and a small receiver in comparison to non-concentrating lens and a thermopile.

(a) Overview alignment control

(b) Alignment close up

(c) Overview spot size on receiver disk

(d) Spotsize close up

Figure 4.9: The sun spot should allineate with the center bore for perfect alignment

4.2 Tracking System

It is necessary to track the sun throughout the day for measuring direct beam radiation. If the system is used as an autonomous system, then the declination angle needs to be adjusted automatically too. The tracking system built for the ESC-MG-2 is equipped with two stepper motors, therefore allowing the system to operate autonomously. Motor drivers/controllers control the motion of the stepper motors and translate the signals given from a LabView program. Figure 4.10 shows the double axis tracking system used for the ESC-MG-2 pyrheliometer.

Figure 4.10: Tracking System for the ESC-MG-2 pyrheliometer

4.2.1 Motors

High torque stepper motors from Anaheim Automation, Inc. are used to adjust the pyrhelimeter. After careful evaluation of the torque and step angle required, stepper motor 17Y402S-LW4 with a step angle of 1.8° and a peak torque of 0.7 Nm was chosen. Figure 4.11(a) shows the stepper motor used.

Figure 4.11: High Torque Stepper Motor from Anaheim Automation

A motor cover was designed to protect the stepper motors from environmental influences like rain. Thermally high conductive adhesive (LOCTITE[®] 383) was used to glue the motor cover to the stepper motor as seen in Fig. 4.11(b). This ensures a good heat transfer from the stepper motor to the motor cover to prevent the motor from overheating. The Stepper motor for the declination angle is wired through a bore in the crank shaft to avoid an external connection. However, this leads to a restriction in the amount of rotation possible before the wires block the rotation. To prevent this, a mechanical limit can be implemented to allow the crank shaft to rotate only $\pm 120^\circ$ based on the solar noon position.

4.2.2 Motor Drivers/Controllers

A motor driver and controller is needed for the communication between the motion controlling LabView program and each of the motors. Two Phidgets Stepper Motor Controller M-200-P1063 from Trossen Robotics were used to control the position and the velocity of each of the stepper motors. Communication is done via USB connection and a Phidgets library containing LabView programs for various motors was utilized. The positioning resolution of these controllers is $1/16^{th}$ step (40-bit signed), which means that this controller is capable of micro-stepping. Recalling here the physical step angle of 1.8° of the stepper motor, the actual step size is $1.8^\circ/16 = 0.1125^\circ$. Two 12 V power supplies P-WM-P3024 from Trossen Robotics were purchased to power the motor controllers.

Figure 4.12: Bipolar stepper motor controller

4.3 Data Acquisition

A LabView program controls the double axis tracking by calculating the position of the sun with respect to a horizontal, south facing observer. In addition, the program writes the measured value to a spreadsheet file for data analysis. A USB-6210 multifunction data acquisition module with a 16-bit resolution and an adjustable input range from ± 0.2 V to ± 10 V was used as seen in Fig. 4.13.

Figure 4.13: USB-6210 multifunction data acquisition module

A thermistor was used for the cold junction compensation. The thermistor used is a low voltage temperature sensor from Analog Devices of the type TMP37. Their typical accuracy is $\pm 1^\circ\text{C}$ at 25°C . The data acquisition has been configured for differential acquisition with an input range of ± 0.2 Volt for the Eppley NIP, and for the temperature measurements of the receiver disk, the collimating tube and the air temperature using K-type thermocouples. The input range for the thermistor used as cold junction temperature was set to ± 1 Volt. The resolution of the measurements is summarized in Table 4.2 and the calculation was done using the same procedure as shown here for the Eppley NIP.

$$\frac{\text{Input range specified}}{(2^{16} - 1) \text{ bit}} = \frac{0.4 \text{ V}}{65535 \text{ bit}} = 6.104\mu\text{V/bit} \quad (4.1)$$

The Eppley NIP has a calibrated response of $8.08\mu\text{V/W/m}^2$, which yields a measurement resolution in terms of W/m^2 as

$$\frac{\text{Voltage per bit}}{\text{Calibrated response of Eppley NIP}} = \frac{6.104\mu\text{V/bit}}{8.08\mu\text{V/W/m}^2} = 0.755 \text{ W/m}^2/\text{bit} \quad (4.2)$$

Table 4.2: Resolution of irradiance and temperature measurements

Input type	Input range	Resolution per bit
Eppley NIP	$\pm 0.2 \text{ V}$	0.755 W/m^2
Thermocouples Type K	$\pm 0.2 \text{ V}$	$1.53 \times 10^{-3} \text{ }^\circ\text{C}$
Thermistor TMP37	$\pm 1 \text{ V}$	$1.45 \times 10^{-4} \text{ }^\circ\text{C}$

The standard deviation was determined from the experimental data. Figure 4.14(a) shows the instantaneous irradiance of the Eppley NIP and ESC-MG-2-F4 with a moving average fit of 30 points for the ESC-MG-2-F4. A close up view can be seen in Fig. 4.14(b), from which the standard deviation was determined. In the same manner, the standard deviation for ESC-MG-2-F2 was determined as seen in Fig. 4.15(a) and 4.15(b). For both instruments, the standard deviation is 1.5 W/m^2 .

Aside from controlling the tracking, the LabView program also writes the temperatures of the receiver disk, the air inside and the collimating tube surface to a spreadsheet file. Figure 4.16 shows the front panel with the inputs: geographic latitude, longitude of location and standard longitude. These three inputs are used to determine the solar time at the location with respect to the location time. In addition, it is necessary to know if daylight saving time is active or not as the difference between the solar time and the standard local time depends on that. Figure 4.17 contains plots of the different temperatures and the corresponding irradiance of the Eppley NIP and the ESC-MG-2.

(a) Irradiance measured with Eppley NIP and ESC-MG-2-F4 with an added moving average over 30 points

(b) Close up view of irradiance and moving average over 6 minutes to determine standard deviation

Figure 4.14: Determination of the standard deviation for the instantaneous irradiance measurements with the ESC-MG-2-F4

(a) Irradiance measured with Eppley NIP and ESC-MG-2-F2 with an added moving average over 30 points

(b) Close up view of irradiance and moving average over 6 minutes to determine standard deviation

Figure 4.15: Determination of the standard deviation for the instantaneous irradiance measurements with the ESC-MG-2-F2

Figure 4.16: LabView front panel inputs

Figure 4.17: LabView front panel graphs

4.4 Offsets of DAQ Boxes

Data acquisition (DAQ) boxes need to be calibrated against a precision voltage power supply. Over time, however, the reference voltage of the DAQ boxes shift and an offset can be observed. Measurements in the solar park were obtained with a USB DAQ box which was located outside for about 2 years, but protected from rain. Comparing these results with the results obtained on top of the Meteorology building, an offset was detected. Further investigations were done performing measurements in the solar park using three different DAQ boxes. Figure 4.18 shows that the temperature offset is about 6.5°C when switching from the DAQ box 2 used in the solar park to the new DAQ boxes 1 and 3.

Figure 4.18: Offset in irradiance and temperature reading between three different DAQ boxes

The values measured with DAQ box 1 and 3 agree, thus concluding that the values measured with DAQ box 2 are offset. As a result of this offset, the irradiance readings with

the DAQ box 2 from the Eppley NIP differ by about 30-40 W/m². On the other hand, the irradiance measured with the ESC-MG-2 is not affected by the offset. This is because it calculates the irradiance according to the temperature difference of two individually measured values, thus cancelling the offset. From the thermocouple table, the voltage corresponding to the temperature shift can be found:

$$\left. \begin{array}{l} 10^{\circ}\text{C} \Rightarrow 0.798\text{mV} \\ 16.5^{\circ}\text{C} \Rightarrow 1.06\text{mV} \end{array} \right\} = \Delta 0.262\text{mV}$$

The conversion constant for the Eppley NIP used is 8.08 μ V per W/m², resulting in

$$0.262\text{mV} \Rightarrow 33 \frac{\text{W}}{\text{m}^2}$$

To compare the results measured with the DAQ box 2 located inside the solar park with the results obtained with DAQ box 1 on top of the Meteorology Building, 33 W/m² were subtracted from the all the Eppley pyrliometer data measured with the DAQ box 2. Figure 4.19 shows that the offset corrected irradiance of DAQ box 2 agrees with the values of the other two DAQ boxes. All of the Eppley NIP data obtained with the DAQ box 2 and presented in Chapter 5 was offset corrected by 33 W/m².

Figure 4.19: Offset corrected irradiance readings of three DAQ boxes

4.5 Setup Configurations

Depending on the location where the pyrliometer is used, the controller box needs to be tilted to an angle corresponding to the latitude with respect to the face normal of the ground plate. This can be done by setting it up at 0° with the use of the reference bore as seen in Fig.4.20(a). The next step is to determine the horizontal position for the pyrliometer holder through the use of the tubular level and the stepper motor control program. Figure 4.20(b) shows how the zero position for the declination stepper motor and the hour angle stepper motors are found. Once this position is referenced as the zero position, the latitude angle can be divided by the step angle of the micro-stepping process to obtain the number of steps to be moved. In this work, the number of steps from the horizontal reference position to the desired latitude angle is,

$$\text{Number of steps} = \frac{\text{Tallahassee Latitude}}{\text{Step angle}} = \frac{30.45}{0.1125} = 271 \quad (4.3)$$

The declination stepper motor then rotates 271 steps, as seen in Fig. 4.20(c). Next, the controller box is tilted as seen in Fig. 4.20(d) until the tubular level indicates a horizontal position as seen in Fig. 4.20(e) . Tightening the screws will fix the position desired for the latitude of the location. Rotating the declination stepper motor backwards by 271 steps yields the zero reference position for the declination angle and the hour angle calculations. Figure 4.20(f) shows the controller box tilted at the latitude angle with both stepper motors at their zero reference position. By adjusting the declination angle and the hour angle, the pyrliometer follows the sun throughout the day measuring the direct normal irradiance.

(a) Horizontal reference position obtained by using a dowel inserted into a reference bore

(b) Set declination angle and hour angle stepper motors to horizontal reference position

(c) Rotate stepper motor by 271 steps so that the pyrheliometer is tilted by the latitude of location

(d) Rotate controller box until tubular level indicate horizontal position

(e) Tubular level close-up for tilted at latitude

(f) Tilted reference position for hour angle = 0 and declination angle = 0

Figure 4.20: Setup configurations for tilting controller box at latitude angle

CHAPTER 5

RESULTS

The results presented here contain information about the chosen focal numbers of the lens, the different motors tested for the tracking system, and the cost of the pyrheliometer including the tracking system. Preliminary results are presented for lenses with four different focal numbers, F#8, F#6, F#4 and F#2. From these results, it was observed that the most accurate setup configuration was with the focal number F#4 and F#2. Following the preliminary results, this chapter presents data which was obtained from extensive testing with the focal numbers F#4 and F#2.

5.1 Preliminary Results to Determine Ideal Focal Number and Ideal Motor for Tracking System

Testing on four different focal lengths F#8, F#6, F#4 and F#2 was done to investigate the influence of the collimating tube length and the accuracy depending on the temperature difference between the receiver disk and the collimating tube. Table 5.1 shows the back focal length of the four lenses tested, their corresponding receiver size and temperature difference

Table 5.1: Temperature difference between receiver disk and and collimating tube of four different focal lengths

Focal #	Back Focal Length	Receiver Diameter	ΔT @ 1000 W/m ²
2	45.8 mm	5.4 mm	67° C
4	97.2 mm	9.4 mm	63° C
6	148 mm	13.6 mm	41°C
8	199 mm	18 mm	26°C

Figure 5.1: Testing of ESC-MG-1-F#8 pyrhelimeter with focal number 8 and preliminary tracking prototype

for an irradiance of 1000 W/m^2 . All of the tested pyrhelimeters yielded results within $\pm 5\%$. However, due to the higher temperature difference for the smaller focal number setup, it was decided to focus only on the focal number 4 and focal number 2 for further design improvements. For the preliminary tracking system, two different types of motors were tested: Stepper motors from Anaheim Automation and hobby servo motors from Hitec. The tracking tests were performed using the longest pyrhelimeter with the focal number 8. Both motors tracked the sun well. However, due to the relatively big backlash of the servo motor, it was decided to proceed with the stepper motors from Anaheim Automation. Figure 5.1 shows the setup with the pyrhelimeter F#8 and a preliminary tracking system using stepper motors.

5.2 Results F#4

In determining the direct beam radiation, I_b , it was seen from the general lumped capacity equation at steady state, Eqn.3.12, that there are two undetermined constants η_{opt} and h_{eff} .

$$I_b = \frac{h_{eff} A_r (T_r - T_\infty)}{\alpha \eta_{opt} A_l}$$

The optical efficiency can be ignored in a first step by looking at the transient cooling characteristic of the system by blocking the incoming irradiance completely. Recalling here the simplified Equation 3.10, noting that $I_b = 0$ and ignoring the conduction term, the following ordinary differential equation describing the transient cooling results:

$$\frac{dT_r}{dt} = -\frac{h_{eff} A_r (T_r - T_\infty)}{m_r c_p} \quad (5.1)$$

This equation can be solved using the boundary condition $T_r(t = 0) = T_o$ and yields

$$T_r(t) = T_\infty \left[1 - e^{-\frac{h_{eff} A_r}{m_r c_p} t} \right] + T_o e^{-\frac{h_{eff} A_r}{m_r c_p} t} \quad (5.2)$$

where T_o is the initial temperature of the receiver at $t = 0$. Comparing experimental data with the lumped capacity model of Equation 5.2, the effective heat transfer coefficient h_{eff} can be calculated iteratively. Figure 5.2 shows the cooling curves of the model using different h_{eff} and compares it with experimental data obtained using the lens with focal number F#4. The value of h_{eff} just determines the shape of the cooling curve. It is unlikely that the experimental data will fit the model perfectly and therefore, the user has to decide at what temperature difference the data best matches the model. In this work, with a chosen value of $h_{eff} = 18$, the model agrees with the experimental data very well during the first 100 seconds.

Once h_{eff} has been determined, the optical efficiency can be iteratively obtained by comparing with experimental data. Figure 5.3 shows the heating curves of the lumped capacity model with various optical efficiencies and compares it with experimental data.

Figure 5.2: Determination of h_{eff} from transient cooling characteristic of experimental data and lumped capacity model for F#4

The best matching optical efficiency for the focal number F#4 is 46.6%. Recalling the discussion of acrylic lenses with a coating for the visible range of the solar radiation, the estimated optical efficiency was about 58%. The discrepancy can be explained by the fact that absorption was considered to be negligible and the reflectivity between 380 and 800 nm was taken as zero.

Now that all of the parameters have been determined, they can be combined into a single parameter that yields the final equation characterizing the ESC-MG-2-F#4 pyrheliometer.

$$\begin{aligned}
 I_b &= \frac{h_{eff} A_r (T_r - T_\infty)}{\alpha \eta_{opt} A_l} = \frac{18 \times 1.53499 \times 10^{-4}}{0.9 \times 0.466 \times 3.7912 \times 10^{-4}} (T_r - T_\infty) \\
 &= 17.39 (T_r - T_\infty)
 \end{aligned} \tag{5.3}$$

Averaged over 8 test runs, the constant was slightly adjusted to 17.35.

Figure 5.3: Determination of η_{opt} from transient heating characteristic of experimental data and lumped capacity model for F#4

5.2.1 Measurements for a sunny day for F#4

(a) Measurements of instantaneous irradiance

(b) Detailed view of the instantaneous irradiance

(c) Irradiation of the Eppley NIP and the ESC-MG-2-F4 and its relative error

Figure 5.4: Comparison of instantaneous irradiance of ESC-MG-2-F4 and Eppley NIP on a sunny day

Figure 5.4(a) shows the instantaneous irradiance of the Eppley NIP and the ESC-MG-2-F3 for a very clear day from 10 AM until almost 5 PM. Looking at the more detailed view as shown in Fig. 5.4(b), one can see that both values are within 20 W/m² or 2%. Integrating the irradiance over the course of the day results in the irradiation value. Figure 5.4(c) show that the irradiation measured with the ESC-MG-2-F4 is about 5.62 kWh/m² for the time between 10 AM and 5 PM and is 0.07 kWh/m², or 1.2% off the integrated value of the Eppley NIP.

5.2.2 Measurements for partly cloudy day for F#4

(a) Measurements of instantaneous irradiance

(b) Detailed view of the instantaneous irradiance

(c) Irradiation of the Eppler NIP and the ESC-MG-2-F4 and its relative error

Figure 5.5: Comparison of instantaneous irradiance of ESC-MG-2-F4 and Eppler NIP on a partly cloud day with a clear morning and upcoming clouds in the afternoon

This day represents a typical summer day in Florida, with very clear mornings and incoming clouds in the afternoon. Figure 5.5(a) shows how the instantaneous irradiance drops drastically after 2 PM. Performing measurements in a transient state, it can be seen in Fig. 5.5(b) that the instantaneous values of the ESC-MG-2-F4 are time delayed in comparison to Eppler NIP. Figure 5.5(c) shows that the relative error of the irradiation measured with the ESC-MG-2-F4 is only 0.57% compared with the Eppler NIP.

5.2.3 Measurements for a mostly cloudy day for F#4

(a) Measurements of instantaneous irradiance

(b) Detailed view of instantaneous irradiance

(c) Irradiation of the Eppler NIP and the ESC-MG-2-F4 and its relative error

Figure 5.6: Comparison of instantaneous irradiance of ESC-MG-2-F4 and Eppler NIP on a day with quickly alternating sun and clouds

From Fig. 5.6(a), it can be seen how quickly the irradiance alternates between zero and 800-900 W/m². After 2 PM, it was completely cloudy and therefore, the measurement was stopped. Figure 5.6(b) shows the time delayed response of the ESC-MG-2-F4 compared with the Eppler NIP. Integrating the irradiance over the time measured yields an irradiation of only 0.93 kWh/m², which is more than 9% off compared with the irradiation of the Eppler NIP. However, a mostly cloudy day as seen here is less than ideal for CSP applications, thus making this relatively big error less significant.

5.2.4 Measurements for large zenith angles F#4

(a) Measurements of instantaneous irradiance

(b) Detailed view of instantaneous irradiance

(c) Irradiation of the Eppley NIP and the ESC-MG-2-F4 and its relative error

Figure 5.7: Comparison of instantaneous irradiance of ESC-MG-2-F4 and Eppley NIP at large zenith angles

Figure 5.7(a) shows the instantaneous irradiance from sunrise to sunset. It can be seen that the measured irradiance of the ESC-MG-2-F4 agrees well even at high zenith angle early in the morning and later in the afternoon. A tall pole located close to the setup on top of the Meteorology building caused time delayed shading around 4 PM. The difference in irradiance between both instruments as shown in Fig. 5.7(b) is within 15 W/m^2 or about 1.5%. Integrated over the entire day, the irradiation value is very high with 8.76 kWh/m^2 and is about 1% off when compared with the Eppley NIP as shown in Fig. 5.7(c).

5.2.5 Summary F#4

All of the runs and their corresponding conditions are summarized in Table 5.2. The integrated irradiation values of the ESC-MG-2-F4 for all of the eight runs are shown in Fig.5.8. Except for the mostly cloudy day, all of the errors are within $\pm 2\%$ when compared with the Eppley NIP. The error for the mostly cloudy day is significantly higher, which can be explained by the time delayed response of the ESC-MG-2-F4 and the small amount of integrated irradiation. Further testing needs to be done to quantify the behaviour and accuracy of the ESC-MG-2-F4 during mostly cloudy days.

Table 5.2: List of all test runs for focal number 4 and the corresponding conditions

Run #	Date	Time	Conditions
1	02/03/10	10:15 - 4:15	Mostly sunny day with very few clouds
2	02/06/10	10:00 - 2:15	Mostly cloudy day. See Fig.5.6
3	02/08/10	10:00 - 4:00	Perfectly clear day. Data used to find h_{eff} and η_{opt}
4	02/10/10	09:45 - 4:45	Clear day with upcoming clouds at 1:30. See Fig.5.5
5	02/13/10	10:00 - 4:45	Perfectly clear day. Data used to find h_{eff} and η_{opt}
6	02/14/10	10:00 - 4:45	Perfectly clear day. See Fig.5.4
7	02/16/10	03:15 - 6:15	Perfectly clear day.
8	02/17/10	07:30 - 6:15	Very clear day. See Fig.5.7

Figure 5.8: Irradiation values for 6 runs and their relative error compared to the Eppley NIP

5.3 Results F#2

Using the same procedure as for the focal number F#4, the effective heat transfer coefficient h_{eff} was iteratively calculated. Figure 5.9 shows the cooling curves of the lumped capacity model using different h_{eff} and compares it with experimental data. The chosen value of h_{eff} for F#2 is 25. The lumped capacity model agrees especially well with the experimental data after 50 seconds.

Figure 5.9: Determination of h_{eff} from transient cooling characteristic of experimental data and lumped capacity model for F#2

The optical efficiency can be obtained the same way as shown for F#4. Figure 5.10 shows the heating curves of the lumped capacity model with various optical efficiencies and compares it with experimental data. The best matching optical efficiency for the focal number F#2 is only 28.1%. Recalling η_{opt} of the focal number F#4 as 46.6%, it can be seen that the F#2 lens has a significantly lower optical efficiency. The discrepancy can be explained by the fact that the curvature of the F#2 is much larger in comparison to the

F#4 as shown in Fig. 4.6. Therefore, it can be assumed that part of the incoming radiation is reflected. This especially holds true towards the edge of the lens where the angle between the incoming radiation and the surface normal is far away from being zero.

Figure 5.10: Determination of η_{opt} from transient heating characteristic of experimental data and lumped capacity model for F#2

Combining all of the constants into a single parameter yields the final equation characterizing the ESC-MG-2-F#2 pyrheliometer.

$$\begin{aligned}
 I_b &= \frac{h_{eff} A_r (T_r - T_\infty)}{\alpha \eta_{opt} A_l} = \frac{25 \times 5.4476 \times 10^{-5}}{0.9 \times 0.281 \times 37.912 \times 10^{-5}} (T_r - T_\infty) \\
 &= 14.20 (T_r - T_\infty)
 \end{aligned} \tag{5.4}$$

Averaged over 13 test runs, the constant was slightly adjusted to 14.25.

5.3.1 Measurements for a sunny day for F#2

(a) Measurements of instantaneous irradiance

(b) Detailed view of the instantaneous irradiance

(c) Irradiation of the Eppler NIP and the ESC-MG-2-F2 and its relative error

Figure 5.11: Comparison of instantaneous irradiance of ESC-MG-2-F2 and Eppler NIP on a sunny day

Figure 5.11(a) shows the instantaneous irradiance over the course of the day. The alternating irradiance before 10:15 AM was caused by shading of a tree. As a result of the setup, one instrument might have been exposed to the sun while the other was still shaded. However, both instruments were exposed to the sun the same amount of time, just time delayed. The difference in instantaneous irradiance between the ESC-MG-2-F2 and the Eppler NIP was about 10 W/m^2 or about 1%, as shown in Fig. 5.11(b). The integrated irradiation of the ESC-MG-2-F2 agreed especially well with the value obtained with the Eppler NIP, as can be seen in Fig. 5.11(c), and had an error of only 0.23%.

5.3.2 Measurements for a partly cloudy day for F#2

(a) Measurements of instantaneous irradiance

(b) Detailed view of the instantaneous irradiance

(c) Irradiation of the Eppler NIP and the ESC-MG-2-F2 and its relative error

Figure 5.12: Comparison of instantaneous irradiance of ESC-MG-2-F2 and Eppler NIP on a sunny day with upcoming clouds in the afternoon

The instantaneous irradiance shown in Fig.5.12(a) represents the typical summer day in Florida. Looking at the detailed view of the irradiance in Fig.5.12(b), it can be seen that the difference in instantaneous irradiance between the ESC-MG-2-F2 and the Eppler NIP was about 5-10 W/m² during the clear part of the day. However, the incoming clouds in the afternoon caused the instantaneous measurements to be time delayed. Figure 5.12(c) shows that the integrated irradiation of the ESC-MG-2-F2 is about 2.2 kWh and has an error of 1.83% when compared with the Eppler NIP.

5.3.3 Measurements for a mostly cloudy day for F#2

(a) Measurements of instantaneous irradiance

(b) Detailed view of the instantaneous irradiance

(c) Irradiation of the Eppley NIP and the ESC-MG-2-F2 and its relative error

Figure 5.13: Comparison of instantaneous irradiance of ESC-MG-2-F2 and Eppley NIP on a day with quickly alternating sun and clouds

In Fig. 5.13(a), it can be seen that the instantaneous irradiance fluctuates significantly. As a result of that, the irradiance measured with the ESC-MG-2-F2 is time delayed as can be seen in Fig. 5.13(b). However, the interest is in the integrated irradiation of the ESC-MG-F2 anyway, which has an error of 0.88% compared with the Eppley NIP, and can be seen in Fig. 5.13(c).

5.3.4 Measurements for large zenith angles F#2

(a) Measurements of instantaneous irradiance

(b) Detailed view of the instantaneous irradiance

(c) Irradiation of the Eppley NIP and the ESC-MG-2-F2 and its relative error

Figure 5.14: Comparison of instantaneous irradiance of ESC-MG-2-F2 and Eppley NIP at large zenith angles

Figure 5.14(a) shows the instantaneous irradiance obtained on top of the Meteorology building from sunrise to sunset. It can be seen that the measured irradiance of the ESC-MG-2-F4 agrees well during the middle of the day as seen in Fig. 5.14(b), but yields slightly higher values at large zenith angles early in the morning and later in the afternoon. Between 8:15 and 8:45, no data was acquired as the computer had crashed. In addition, time delayed shading around 4 PM was caused by a tall pole located close to the setup. Integrated over the entire day, the irradiation value is very high with 8.51 kWh/m² and is off by about 1.8% when compared with the Eppley NIP, as shown in Fig. 5.14(c).

5.3.5 Summary F#2

All of the runs and their corresponding conditions are summarized in Table 5.3. The integrated irradiation values of the ESC-MG-2-F2 of all of the thirteen runs are shown in Fig. 5.15. Except for run 8 with some cloud cover, the irradiation values are within $\pm 2\%$ when compared with the Eppley NIP. The error for run 8 was almost 4% while run 12, which was a mostly cloudy day, yielded an error of less than 1%. It is recommended to do further testing to quantify the behaviour and accuracy of the ESC-MG-2-F2 during mostly cloudy days.

Table 5.3: List of all test runs for focal number 2 and the corresponding conditions

Run #	Date	Time	Conditions
1	01/22/10	10:15 - 2:45	Perfectly clear day
2	01/23/10	1:15 - 4:15	Clear day with upcoming clouds at 3:30 pm. See Fig. 5.12
3	01/25/10	10:15 - 4:15	Cloudy until 11:15, then a perfectly clear day
4	01/26/10	09:45 - 4:15	Shading of trees before 10:15, then a very clear day
5	01/27/10	09:45 - 4:15	Shading of trees before 10:15, then a very clear day. See Fig. 5.11
6	01/28/10	10:15 - 4:15	Mostly cloudy day
7	02/18/10	07:30 - 6:15	A clear day with a few clouds after 4:30. See Fig. 5.14
8	02/19/10	07:30 - 6:00	Clear day with clouds from 9:00-11:00 and 3:30-6:00
9	02/20/10	01:30 - 4:45	Perfectly clear day. Data used to find h_{eff} and η_{opt}
10	02/25/10	10:30 - 4:30	Perfectly clear day
11	02/26/10	09:30 - 4:30	Clear day with hazy sky in the afternoon
12	03/01/10	10:45 - 4:45	Mostly cloudy day with some sun in the afternoon. See Fig. 5.13
13	03/03/10	10:45 - 4:00	Perfectly clear day. Data used to determine offset between DAQ boxes. See Fig. 4.18 and 4.19

Figure 5.15: Irradiation values for 13 runs and their relative error compared to the Eppey NIP

5.4 Cost

One of the main goals of this work was to keep the cost of the pyrheliometer and the tracking system below \$500. For the prototype manufactured and assembled at ESC, the cost was estimated to be about \$1000. The main parts where the cost can be reduced are the stepper motor controllers and the machining expenses. If produced in large quantities, the cost of the machining would reduce from \$950 for a single pyrheliometer to about \$475 for 50 units. Some of the parts can be cast, thus reducing the cost even further when producing in large quantities. In addition, some of the aluminum parts can be replaced by plastic.

CHAPTER 6

CONCLUSION

From the results obtained for both the ESC-MG-2-F2 and ESC-MG-2-F4 it can be concluded that a low cost pyrhelimeter including tracking system was successfully designed, built and tested. The time response of the ESC-MG-2-F2 and ESC-MG-2-F4 is about 125 and 150 seconds, respectively. The accuracy for both of the tested instruments for the integrated irradiation is within $\pm 2\%$ compared with the Eppley NIP. The steady state instantaneous irradiance of the ESC-MG-2-F2 and ESC-MG-2-F4 agrees well with the Eppley NIP, but they are time delayed for transient measurements. Due to the low optical efficiency of the F#2 lens, the F#4 instrument is recommended as a first choice. Considering the cost of at least \$5000 for a field pyrhelimeter, the ESC-MG-2-F4 costs significantly less with an estimated cost of around \$700 if produced in quantities of at least 50. Overall, it can be said that the ESC-MG-2-F4 is a low cost pyrhelimeter in the range of \$700 with an accuracy of $\pm 2\%$ for irradiation values.

6.1 Future Work

The following future work suggestions are meant to increase the accuracy, simplify the system and increase the chances to introduce it to the market:

- Testing of an uncoated acrylic lens should increase the optical efficiency by about 20%, thus increasing the temperature of the receiver and therefore increasing the resolution.
- Instead of reading the voltage of both thermocouples individually, they can be connected in series. The so called differential pair of thermocouples creates an emf corresponding to the temperature difference of the receiver disk and the collimating tube surface.

- Include a voltage amplifier for the voltage created by the differential pair of thermocouples
- Replace thermocouple plugs by a circular multi-pin connector and a regular copper lead cord.
- Implement mechanical limit for hour angle rotation axis
- Optimize the choice of material and specify parts which can be cast.
- Design of a stepper motor controller and driver including a processor and data logging unit.

APPENDIX A

OPTICS

Figure A.1: Anti reflective coatings for various wavelengths specifications: Courtesy of Edmund Optics

Figure A.2: Reflectivity of VIS coated lens: Courtesy of Edmund Optics

Figure A.3: Transmittance of uncoated acrylic lens: Courtesy of Edmund Optics

APPENDIX B

CAD DRAWINGS OF PYRHELIOMETER

Figure B.1: ESC-MG-2-F2 Pyrheliometer

Figure B.2: Exploded view of ESC-MG-2-F2 Pyrheliometer

Figure B.3: CAD drawing of Top Flange

Figure B.4: CAD drawing of Tube Top Attachment

Figure B.5: CAD drawing of Collimating Tube F#2

Figure B.6: CAD drawing of Collimating Tube F#4

Figure B.7: CAD drawing of Tube Bottom Attachment

Figure B.8: CAD drawing of Copper Receiver Disk F2

Figure B.9: CAD drawing of Copper Receiver Disk F4

Figure B.10: CAD drawing of Bottom Flange

Figure B.11: CAD drawing of Bottom Flange Cover

APPENDIX C

CAD DRAWINGS OF TRACKING SYSTEM

Figure C.1: CAD model of Tracking Top

Figure C.2: CAD model of Tracking System Bottom

Figure C.3: CAD model of Tracking System Suppressed

Figure C.4: CAD drawing of Ground Plate

Figure C.5: CAD drawing of Side Plate

Figure C.6: CAD drawing of Controller Box

Figure C.7: CAD drawing of Controller Box Cover

Figure C.8: CAD drawing of Controller Box Window

Figure C.9: CAD drawing of Motor Cover Hour Angle

Figure C.10: CAD drawing of Motor Cover Lid

Figure C.11: CAD drawing of Aluminum Crank Shaft

Figure C.12: CAD drawing of Crank Shaft Attachment

Figure C.13: CAD drawing of Declination Bearing Holder

Figure C.14: CAD drawing of Declination Motor Holder

Figure C.15: CAD drawing of Motor Cover Declination Angle

Figure C.16: CAD drawing of Axis Declination Motor

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Figure C.17: CAD drawing of Pyrheliometer Holder

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In the fall of 2005, Michael Gnos completed his Bachelors degree in Mechanical Engineering at the University of Applied Science in Rapperswil, Switzerland . Under the advisement of Prof. Anjaneyulu Krothapalli, he obtained his Master's degree in Sustainable Energy in the spring of 2010 from the Department of Mechanical Engineering at Florida State University.

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