Characterization of Pyranometer Thermal Offset and Correction of Historical Data

Bernardo A. Carnicero Domínguez

Thesis submitted to the Faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Master of Science

in

Mechanical Engineering

Dr. Martial P. Haeffelin, Chair

Dr. J. Robert. Mahan

Dr. Elaine P. Scott

June 15, 2001

Blacksburg,Virginia

Keywords: Pyranometer, Thermal Offset, Pyrgeometer, Correction of Data, Cloud Cover Fraction, net IR

Characterization of Pyranometer Thermal Offset and Correction of Historical Data

Bernardo Carnicero

(Abstract)

The Eppley Precision Pyranometer (PSP) is a radiometer used in networks around the world to measure downwelling and upwelling diffuse and total hemispherical broadband solar irradiances. PSP's present an offset in the signal, called thermal offset, produced by a radiation heat exchange between the glass dome, which defines the spectral throughput and the detector. This offset can reach up to 15% of the total value of the signal when measuring diffuse irradiance under clear sky conditions. The thermal offset is characterized by monitoring the temperature gradient between the dome and detector using thermistors at key locations. The temperatures are acquired by using thermistors. Relationships between the thermal offset and the temperature gradient are established using nighttime data and subsequently used to estimate the offset during daytime. To correct historical data the thermal offset is related to other variables such as the output of a Precision Infrared Pyrgeometer (PIR) or the fraction of cloud cover in the sky. The use of thermistors is a very reliable method to estimate and correct the thermal offset. The relationships between the offset and the IR output and between the offset and the cloud cover fraction provide good estimates of the thermal offset in historical data sets, reducing it 60% to 100% depending on the instrument and the relationship used.

NOMENCLATURE

Symbols:

A1, A2:instrument A1 and instrument A2 as defined by B. Forgan.

C: Instrument sensitivity (V/Wm^{-2}).

CF: Cloud cover fraction

E: Solar irradiance (W/m^2).

netIR: Output of a Pyrgeometer (W/m^2).

Offset: Thermal offset (W/m^2).

R: Responsivity of a PSP as Forgan (V/Wm^{-2}).

S: Seebeck coefficient of thermopile ($\mu V/K$).

T: Temperature

U_e: Thermopile signal (V)

V: Global irradiance signal as defined by B. Forgan

Greek:

α: Absorptivity

λ: Ratio between the difference of daytime and nighttime offset and nighttime offset.

ε: Emissivity

ρ: Reflectivity

σ: Stefan-Boltzman constant

τ: Transmissivity

θ: Solar zenith angle

Subscripts:

0: Particular situation as defined by B. Forgan.

b: Body of a PSP.

body: Body of a PSP.

d: Dome (inner) of a PSP.

id: Inner dome of a PSP

od: Outer dome of a PSP

Day: Daytime conditions.

detector: Detector of the PSP.

Diffuse: Diffuse component of the solar. irradiance.

Direct: Direct component of the solar. irradiance.

Global: Global component of the solar. irradiance.

net: Total.

Night: Nighttime conditions

s: Sensor.

Acknowledgements

Two years ago I took a plane to the US with the aim of getting a Master of Science at Virginia Tech. I knew that this trip would provide me not only technical knowledge but something else. However, when I left Spain I could not suspect that the experience of spending two years of my life studying and working in the US would enrich me so much. Most of this enrichment have come from all the different and exceptional people that I have met during this time. Among all of them I would especially like to thank my advisors Dr. Martial Haeffelin and Dr. J. R. Mahan because if an advisor is the person who gives you advice then what is the English word for the person who patiently teaches you, guides you and treats you not as a student but as an equal. I would like to thank Dr. Elaine Scott for serving on my advisory committe. My work experience at NASA Langley gave me the opportunity to meet some of the most brilliant atmospheric scientists who are doing an amazing work to understand the planet in which we live; I thank all the NASA Langley Atmospheric Science Branch people for their support and kindness, I have been very lucky to work among you. Thank you to all the latin community in Blacksburg they have shown me, again, that there are not two shores but only one sea. Thank you to my friends in Blacksburg and Norfolk, I am going back home richer just from meeting you. And finally thank you to my family and the people that in spite of the distance have always been with me.

Contents

List of Tables

List of Figures

Chapter 1

Nature of the Research

1.1 Background

Climate on Earth is an extremely complex and fascinating thermal and fluid dynamic system. It is a huge puzzle where all the pieces are inter-related. Humans have tried to understand climate, probably since the beginning of humankind. This strong desire of knowledge came from necessity. The ability to predict the starting of seasons, storms or draughts, could make the difference between a period of abundance or a time of starvation, or the decadence of a civilization and the emergence of a new one.

Egyptians, Greeks, Romans, Mayas and the ancient oriental civilizations tried to predict the weather and its consequences on humans, by making sometimes amazing discoveries using only their experience. Today's developed occidental society can predict the weather several days in advance with high accuracy. However the task of making long-term forecast and predict how the climate will be some years from now still remains in the darkness.

Humans have always been concerned about the consequences of climate on their life. However, recently another question emerged: what are the consequences of the human activities on climate? Are the planetary-wide human activities modifying climate on Earth? Both questions are actually strongly related.

Thousands of scientists all over the world, using satellites, world-wide measurement networks, intensive observation programs or multi-decadal datasets, are working to discover the relationships between the variables that affect and force climate on Earth. A lot of impressive achievements have been made but the task of predicting the effects of a human-modified (e.g. agriculture, pollution) climate on human life still remains unknown.

Climate on Earth is driven by the balance of two types of energies, radiation originating from the sun and radiation emitted by the Earth and its atmosphere escaping to space. It is the so-called radiation energy balance. The amount and distribution of solar radiation absorbed and reflected by the Earth-atmosphere system, as well as the amount and distribution of Earth emitted radiation escaping drive the climate. Variables such as atmospheric gases (e.g. carbon dioxide, water vapor), aerosols from volcanic eruptions, erosion or human activities, cloud particles, cloud cover fraction and surface types, just to name a few, affect the energy balance.

Therefore, the first step to understand climate is to measure accurately how much solar energy is absorbed and reflected by the atmosphere and the surface of the Earth, as well as how much energy the Earth-atmosphere system is emitting to the outer space.

1.2 Accuracy of Diffuse Irradiance Measurements

Among all the variables affecting the Earth radiation budget there is one of particular importance: the total broadband solar irradiance incident at the surface of the Earth [25]. This is the amount of radiant energy coming from the sun that is not absorbed nor back-scattered by the atmosphere and hence reaches the surface of the Earth.

The total broadband solar irradiance is important in atmospheric sciences because it is intimately related to the understanding of atmospheric composition, gaseous absorption, molecular and particular scattering and radiative transfer theory [15]. All of these elements provide valuable information to understand the Earth radiation budget and therefore to understand climate, as well.

The total broadband solar irradiance at the surface of the Earth can be measured by remote sensing techniques using instruments on satellites, or by direct measurements on the ground. Ground measurements can be used to validate satellite products.

Ground measurements of the total broadband solar radiation can be done in two different ways: directly or using the so-called component summation technique. The first technique consists of using a radiometer called pyranometer, which is the primary object of study of the present research. Pyranometers were first designed to measure total broadband solar radiation incident on the surface of the Earth. The pyranometer output presents, however, a dependence on the angle of incidence of the incoming radiation. This dependence, called cosine error, can produce a significant error in the measurement. Manufacturers try to minimize the cosine error in the instrument design and in the calibration procedure of the instruments. Although it can be minimized, the cosine error cannot be eliminated completely from the measurement.

A study by the Baseline Surface Radiation Network (BSRN) [23] suggests that important improvements in the total solar irradiance can be achieved by using an indirect technique that can get rid of the directional response problem. This indirect technique consists of measuring the two components of the total (or global) surface solar irradiance separately. The components are the irradiance in the direct solar beam and the solar irradiance scattered by the atmosphere and incident on the surface, called diffuse irradiance. However, the diffuse irradiance is not a simple variable to measure accurately[6].

The cosine response error is reduced when pyranometers are used to measure diffuse irradiances because the incident radiation is not collimated. Therefore pyranometers have been used preferably to measure diffuse irradiances occulting the direct solar beam from the field of view of the instrument. However pyranometers present another type of error reported since its conception. A gradient of temperature through the instrument results in an offset in the output of the instrument. It is called thermal offset. This source of error in the response of the instrument reported by Gulbrandsen in 1978 [10] can be considered negligible when measuring total irradiance because its magnitude is small compared to the total output. It was not considered significant either when pyranometers were originally used to measure diffuse irradiances.

A study by Kato et al. [15] reports an important disagreement between calculations of extinction of the direct solar beam and the quantities measured during clear-sky days of the Atmospheric Radiation Enhanced Shortwave Experiment (ARESE). In addition, in some cases, the amount of diffuse radiation for a clear sky day was less than the amount scattered by a pure atmosphere with no aerosols, which is not possible.

There are only two possibilities to solve the discrepancy between models and measurements [15]:

- The presence of a gas not included in the model that could absorb an amount of radiation equal to the discrepancy or,
- An error in any of the instruments. This error should be something considered negligible but, that in fact is not.

Kato's study provoked a certain commotion in the scientific community and a process to review the accuracy and uncertainties of several radiometer started. The pyranometer came in the spotlight. And the conclusion was that the thermal offset, considered negligible when measuring total irradiance, had an effect on the output of the instrument measuring diffuse irradiance.

The scientific community then, [4, 5, 12, 13, 14, 22, 26, 27] started to characterize and quantify the thermal offset in pyranometers and look for ways to not only correct it in future measurements but also to correct the measurements of diffuse irradiance already collected.

1.3 Goals of the Research

This research started with the intention of improving the accuracy of ground-based measurements of diffuse solar irradiance. There are several ways to accomplish this task. As an example, one can imagine redesigning the instruments or even developing a new more accurate instrument.

However the most practical way to solve the assignment is, without any doubt, first to characterize the sources of errors in the instruments currently used and second to correct them with empirical correlations. This approach also provides valuable information that can be used to correct and update the historical data that have been carefully acquired and stored for years. Thus, it is logical to first address these issues and then address the question of making design modifications in the actual instrument or even replacing them by more accurate ones.

In order to improve the measurement of diffuse solar radiation, which has been a major scientific consideration for some years by the science community, the present research must accomplish three primary goals that are shown in a flow chart in Figure 1.1:

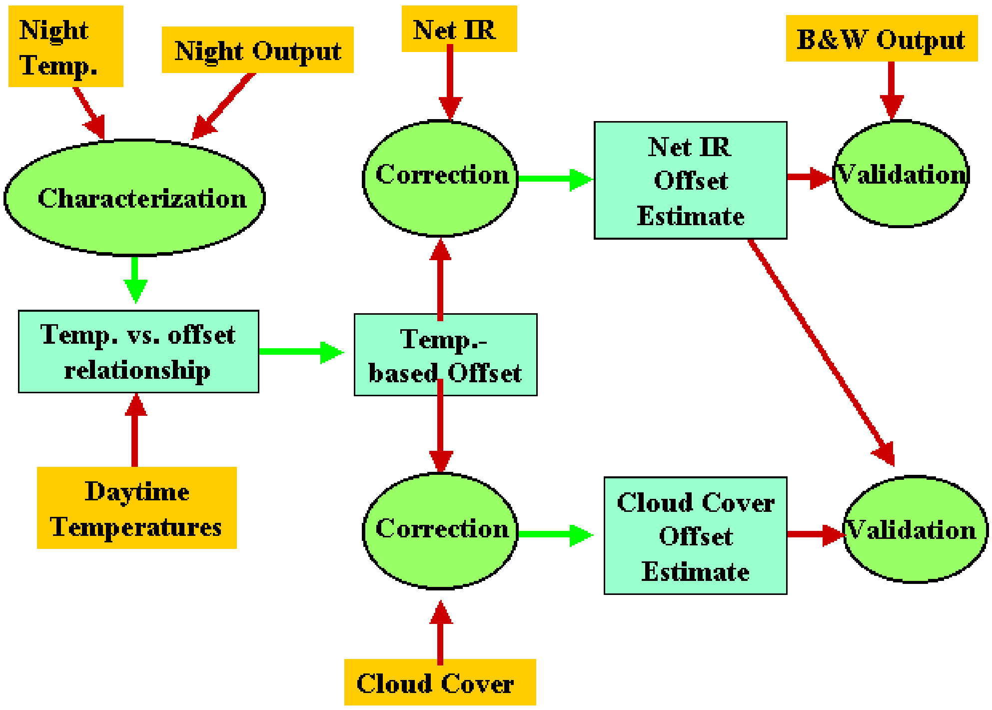

Figure 1.1: Flow chart explaining the goals, plan and steps of the research: characterization of the offset, correction of data using relationships with other parameters, validation of the relationships and correction of historical data

- **Characterization of the thermal offset**: The thermal offset is characterized empirically using nighttime and daytime data. A regular Eppley Precision Spectral pyranometer (PSP) is modified with thermistors to accomplish this task. The thermistors measure the temperature of the components of the instrument that create the thermal offset.

- **Correction of the thermal offset**: The temperature based thermal offset characterized before is used as a reference to derive correlations to correct the offset in non-modified PSP's. The temperatures of the components that create the offset are unknown in non-modified PSP's. The temperature based offset is related to the net IR coming from a Pyrgeometer to find the offset-net IR relationship and to the cloud cover fraction to find the offset-cloud cover relationship.

- **Validation of the relationships**: The relationships derived before are now validated using a real historical.

1.4 Structure of the Dissertation

Chapter 2 gives a full description of the Eppley Precision Spectral pyranometer and an overview of other instruments used in the research such as the pyrgeometer (PIR) and the Normal Incidence Pyrheliometer (NIP). Chapter 2 also describes the data sets used in the research and calibration procedures for the pyranometers. The offset of the PSP is characterized in Chapter 3. Using modified PSP's, an empirical correlation is derived from nighttime data and validated during daytime. The variability of the correlation coefficients for different conditions is also discussed in Chapter 3. Relationships between the PSP offset and other variables are described in Chapter 4. Two different relationships are proposed to correct non-modified PSP's based on the net infrared radiation measured at the surface and the cloud cover fraction. Chapter 5 shows how correlations and results found in previous chapters can be applied to correct historical data. In Chapter 6, the research effort presented in this thesis is summarized, and future work is presented.

Chapter 2

The Instruments

2.1 Description of the instruments

2.1.1 Eppley Precision Spectral Pyranometers (PSP)

The early works in pyranometry were carried out by Abbot and Aldrich in the beginning of the last century (1913) [1]. Ångström made the first successful attempt to build an instrument capable of measuring the direct solar beam (pyrheliometer). Following Ångström's success, Abbot and Aldrich tried to design an instrument "for measuring the solar radiation scattered inward by the sky in daytime". Abbot and Aldrich called the new instrument pyranometer from the greek words $\pi\upsilon\rho$ (fire) $\alpha\nu\alpha$ (up) and $\mu\varepsilon\tau\rho o\nu$ (a measure) signifying "that which measures heat above". Abbot and Aldrich [1] defined their instrument "to measure the energy of radiation to or from a complete hemisphere lying above the measuring surface".

Nowadays the World Meteorological Organization defines the pyranometer as an instrument used to measure solar radiation arriving from a solid angle of 2 π steradians onto a plane surface in the spectral interval of 0.3 to 3 μm, which is a similar definition to Abbot and Aldrich's original definition. Pyranometry has evolved through the years and today several manufactures (Eppley labs, Kipp&Zonen, YES instrument) provide different models of pyranometers based on a variety of design concepts. The Eppley

Precision Spectral Pyranometer (PSP) is used in networks around the world [1] to measure downwelling and upwelling diffuse and total hemispherical broadband solar irradiance.

Figure 2.1 shows a diagram of a PSP. The main components of the instrument are listed below:

- The inner and outer domes; their role is to filter out infrared radiation coming from the atmosphere and the surroundings and to allow shortwave radiation coming from the sun to reach the detector.
- The detector is a thermopile made with more than 40 thermocouples connected in series. The hot junction of the thermopile is coated with a highly absorbing material.
- The body of the instrument is a cylindrical piece of brass painted white to reduce the absorption of solar irradiance. The electrical circuit is mounted inside. The body is used as heat sink for the cold junction of the thermopile.
- The guard disk is a circular piece of metal painted white. It shields the instrument body from downwelling solar radiation.
- The instrument also contains a desiccant to remove the humidity inside the body to protect the circuitry, and a bubble level to guide the leveling of the absorber surface.

A thermopile consists of a fairly large number of thermocouple junctions mounted in series to increase the output signal. The cold junctions of the thermopile are intimately connected to the body of the instrument, which remains at a fairly constant temperature due to its large mass and large thermal capacity. The hot junctions are bonded to a layer of Parson's Black paint, which is a strong radiation absorber at all thermal wavelenghts (α=0.98). The Parson's Black Paint layer absorbs not only solar radiation but also infrared (IR) radiation. To separate solar radiation from IR radiation the detector is covered by a 1-mm inner dome and a 2-mm outer dome made of precision ground polished WG295 Schott optical glass. This glass is transparent to radiation within the 0.285-2.8 μm range (main wavelength interval of solar radiation) and is considered opaque in the IR wavelenghts. Therefore, theoretically, only shortwave radiation coming from the sun is incident on the detector. The absorbed radiation increases the temperature of the hot junction. The temperature gradient between the hot and cold junctions generates a voltage proportional to the incident radiation.

In the absence of any radiation incident on the detector, the hot junctions and the cold junctions remain at the same temperature and the voltage signal is zero. However

[1] Such as the Atmospheric Radiation Measurement (ARM) dependent from the U.S. Energy Department

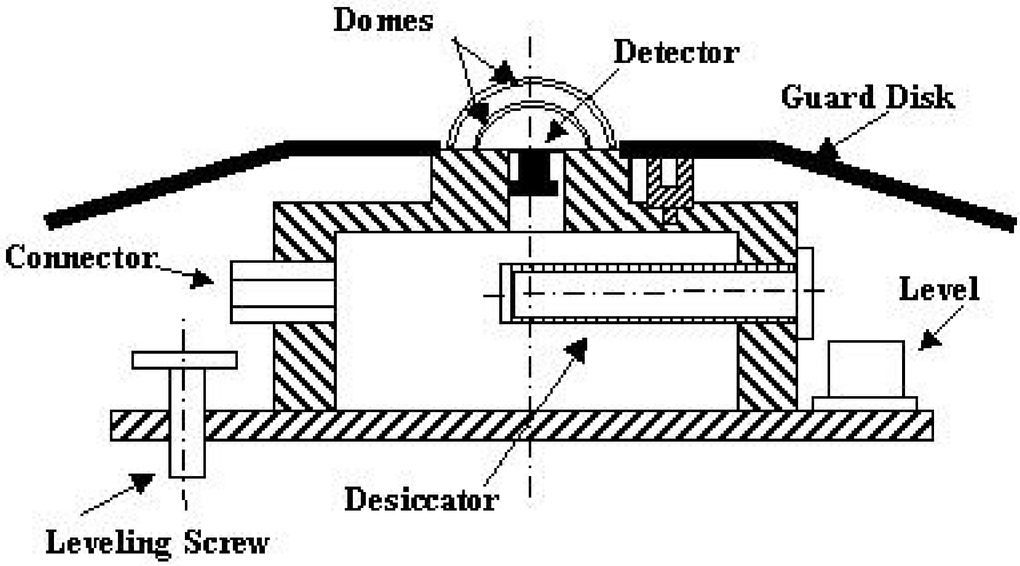

Figure 2.1: Diagram of an Eppley pyranometer. From Lenoble [16]

if the detector is exchanges any kind of radiation the temperature of the hot junctions will change and the output signal will deviate from zero. The detector also exchanges IR radiation with the domes. The amount of radiation emitted depends on the temperatures of the detector and the domes. When the detector absorbs solar radiation its temperature increases and so does the amount of IR emitted. This effect is accounted in calibration. Eppley assures that the temperature dependence of the detector responsivity does not vary more than 1% from its calibration value at 20°C when operating between −20°C and 40°C. However this can be an important issue when the instrument is operating on-board airplanes and balloons at high altitude where the range of temperatures exceeds by far the usual operating range.

The PSP is used to measure global broadband solar irradiance. The PSP can also measure diffuse broadband solar irradiance by shading the instrument from the direct solar beam. To do this, the instrument is mounted on a device called a solar tracker, shown in Figure 2.2, that follows the apparent path of the sun and projects a shadow on the detector, occulting it from the direct solar beam.

2.1.2 Modified PSP

The modified PSP is a regular PSP with one thermistor placed on the dome and another one placed in the body of the instrument. The purpose of these thermistors is to continuously monitor the temperatures of the dome and body. The present research follows the method of Haeffelin et al. [13] to modify a PSP. This method consists of attaching the dome thermistor to the inner surface of the inner dome and the body thermistor inside the heat sink of the detector. Bush et al [4] modify their PSP by attaching the dome thermistor on the outer surface of the outer dome and the body thermistor close to the cold junction of the thermopile.

The thermistor installed in the body of the PSP is a standard YSI 44031; it measures the temperature of the cold junction of the thermopile of the PSP. The thermistor placed on the inner surface of the inner dome is a reduced-size thermistor (YSI SP20796) which has been painted white to minimize the effect of solar radiation on it. This thermistor is bonded to the inner wall of the inner dome with a thermally conductive white silicon paste. This thermistor is placed 40° from the base of the dome; it will measure the radiative temperature of the inner dome. To install the thermistors it is necessary to drill two holes in the body of the instrument. All the procedures of the installation of the thermistors are very delicate tasks. Figure 2.3 shows a modified PSP with two thermistor mounted on it.

The 4-pin connector is replaced by a ten-pin connector so that the thermistor output can be measured. Ideally [13] using these types of thermistors it is possible to measure the temperature variations with a precision of ±0.005°C. From our experience, the temperature difference between the two termistors installed in the instrument can be determined with an uncertainty of $0.05°C$. A $\Delta T = \pm 0.05°C$ corresponds to about $\pm 1 Wm^{-2}$.

2.1.3 Eppley B&W Pyranometer

The Black and White (B&W) pyranometer is an instrument designed to measure diffuse broadband solar irradiance. The B&W pyranometer is a thermopile-based instrument as is the PSP but it differs from the PSP in mainly three design characteristics as is shown in Figure 2.4 shows

- It has only one dome to filter out IR radiation coming from the atmosphere,
- The detector is coated with white and black paint,

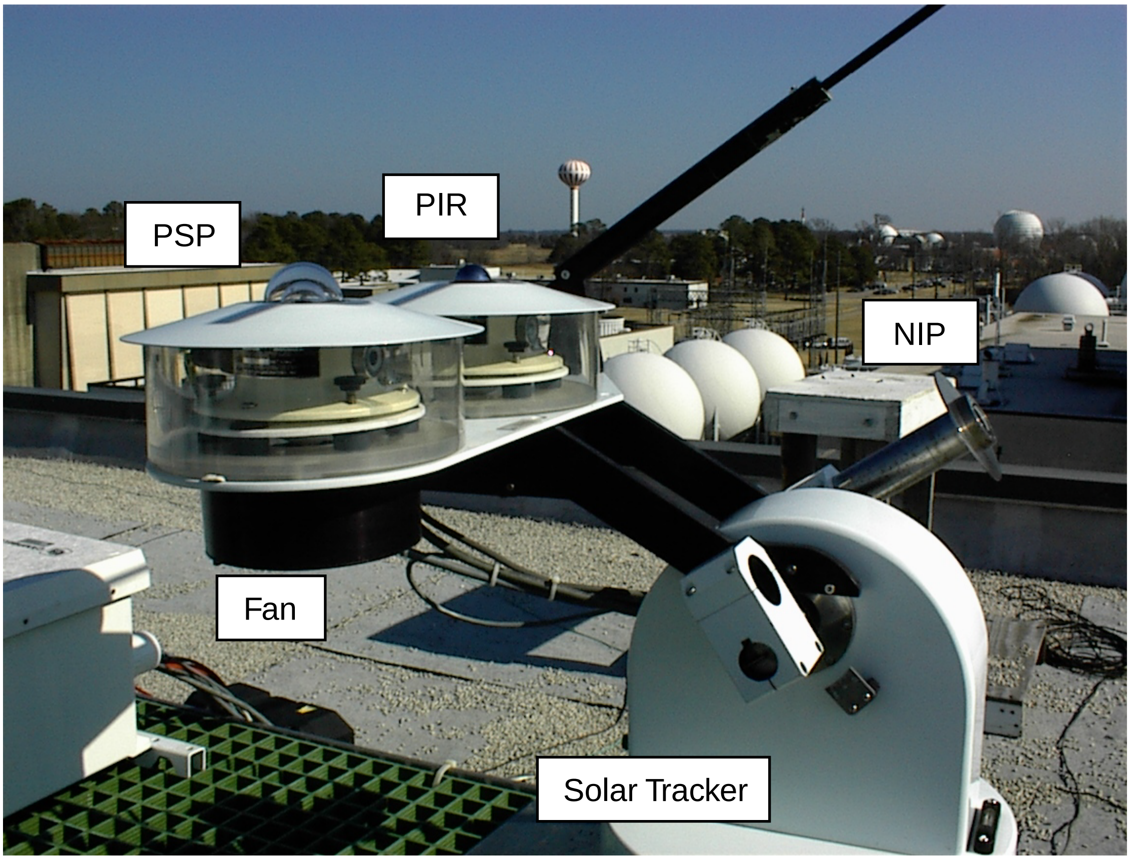

Figure 2.2: Solar tracker with a PSP, a PIR and a NIP at the radiometric site of the NASA Langley Research Center. Note that the white radiation shields are exposed to direct solar radiation, however the domes of the two instruments are shaded

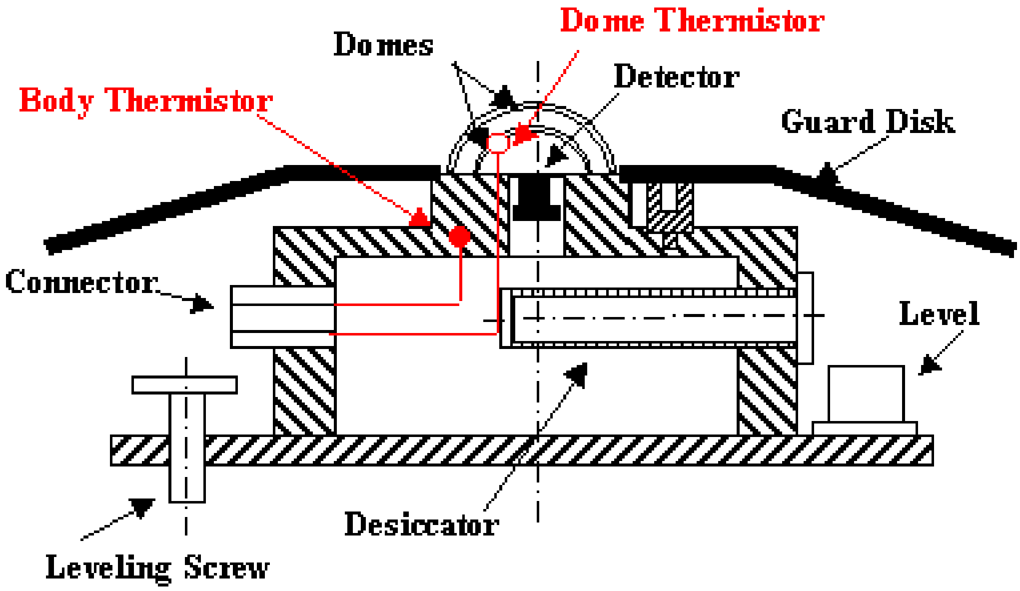

Figure 2.3: Diagram of a modified Eppley pyranometer

- It has much less thermal mass.

The cold junctions of the thermopile are bonded to the white coating of the detector and the hot junctions are bonded to the black coating of the detector. The B&W does not need a large thermal mass to maintain the stability of the cold junctions and hence it is much lighter than a regular PSP. The signal is proportional to the temperature difference between hot and cold junctions. The infrared radiation transmitted through or emitted by the dome affects both types of coatings (white and black paint) the same way. Because IR radiation is absorbed by both types of coatings the IR radiation does not produce any signal. However the signal will be affected by the differential aging of the spectral properties of the black and white coatings. The directional response of B&W is likely to be worse than in a PSP because of the non-uniformity of the detector as is shown in Figure 2.4. The B&W pyranometer has a much longer time response than a regular PSP (see Chapter 3). A regular PSP takes about ten seconds to reach the steady state, meanwhile a B&W pyranometer takes in excess of one minute to reach the same steady

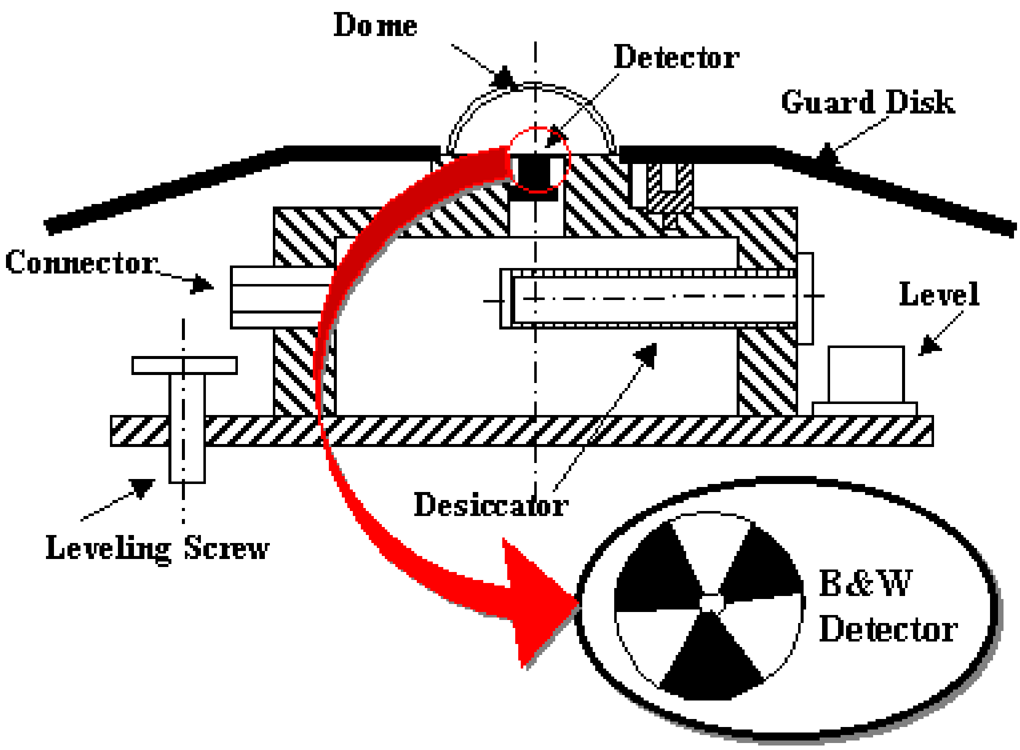

Figure 2.4: Diagram of an Eppley B&W

state.

2.1.4 Eppley Precision Infrared Radiometer (PIR)

The precision Infrared Pyrgeometer (PIR) is an instrument designed to measure hemispherical downwelling or upwelling longwave terrestrial or atmospheric radiation. The first pyrgeometers were designed by Ånström in the beginning of the twentieth century [1]. The word pyrgeometer comes from the Greek words $\pi\upsilon\rho$ (fire) $\gamma\alpha\iota\alpha$ (Earth) and $\mu\varepsilon\tau\rho o\nu$ (a measure) signifying "which measures the fire coming from the Earth". Therefore a PIR measures infrared irradiances coming from the Earth or the atmosphere in the wavelength band ranging from 3.0 to 50 μm. Together the PSP and the PIR cover the wavelength range of interest to study the radiation budget at the surface of the Earth.

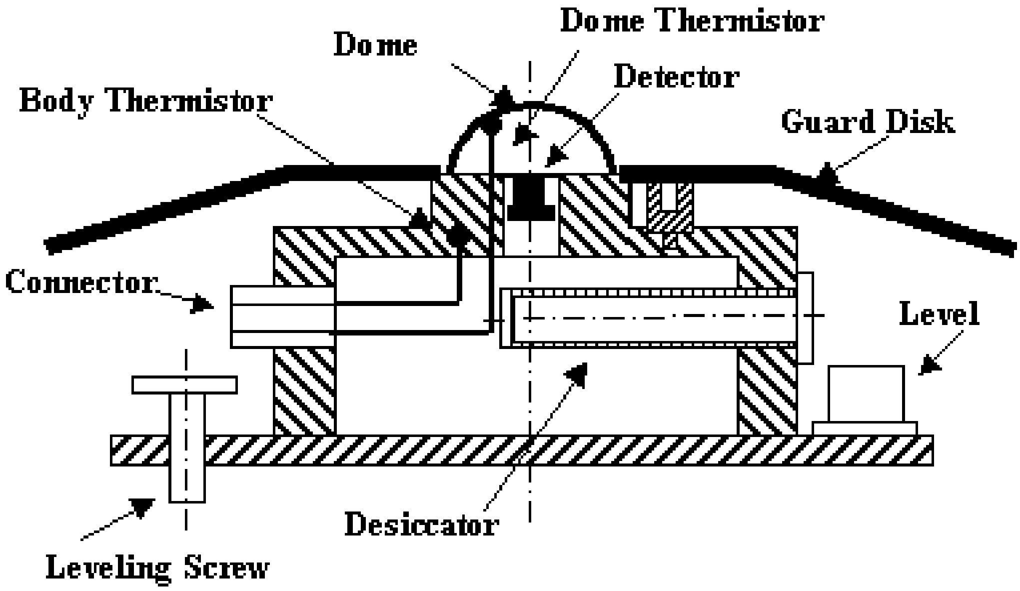

Figure 2.5: Diagram of an Eppley Pyrgeometer

The conceptual design of the PIR is similar to the PSP. Figure 2.5 shows a schematic diagram of a PIR. The PIR also uses a thermopile detector like the PSP. The detector is also covered by a dome that filters out the part of the spectrum not desired to be measured. The dome of a PIR is made of silicon. On the inner surface there is a vacuum deposited interference filter. According to Eppley labs the dome presents a sharp transition at 3.0 μm from completely opaque to maximum transmittance in the infrared. At around 50 μm the transmittance decreases with wavelength. The dome can be considered opaque to solar radiation.

However the PIR also presents a thermal offset, the exchange of radiation between the dome and the body of the instrument is larger than in the PSP. Therefore in order to correct the signal and get rid of the contribution of the radiation heat exchange between dome and body, several thermistors have been installed in the PIR. Two typical configurations are available: a PIR with one thermistor on the dome and one thermistor in the body or a PIR with three thermistors on the dome (facing North, NorthEast and

NorthWest) and one thermistor in the body.

Both shortwave radiation coming from the sun and infrared radiation coming from the atmosphere are incident upon the dome. Most of the shortwave radiation is absorbed by the dome, which increases its temperature. This increase in temperature also implies an increase of radiative energy emitted to the atmosphere and to the detector of the PIR. The output signal of a PIR is, therefore, composed of two terms:

- The downwelling IR from the atmosphere,
- Radiant energy exchange between dome and detector.

The true IR irradiance arriving at the detector can be derived from the instrument signal and the temperature gradient between dome and detector.

2.1.5 Eppley Normal Incident Pyrheliometer (NIP)

A pyrheliometer is an instrument that measures the direct component of the solar beam at normal incidence. Therefore a pyrheliometer must be mounted on a device called a solar tracker that orients the pyrheliometer perpendicular to the solar beam during the day. The word pyrheliometer comes from the Greek words $\pi\upsilon\rho$ (fire) $\eta\lambda\iota o\varsigma$ (sun) $\mu\varepsilon\tau\rho o\nu$ (a measure), signifying "that which measures the fire from the sun".

The first pyrheliometer was design by the Swedish physicics K. Ångström in the beginning of twentieth century [1]. The first pyrheliometer was composed of two strips of blackened manganin at the end of a long narrow tube with a small aperture at one of the ends of the tube. One of the strips was shaded from the sun and the other was exposed. The one exposed to the sun is heated by solar radiation. The one shaded is heated by an electric current that can be varied. When the temperatures of the two strips are equal it is assumed that the energy absorbed by the unshaded strip is equal to the energy dissipated by the current in the shaded one. To eliminate errors the strips are rotated. The same concept is applied in active cavity radiometers used to calibrate NIP's.

The NIP is a simplified design of the first pyrheliometer. Figure 2.2 shows NIP 31375 E6 mounted on a solar tracker. The detector of a NIP is a thermopile located at the base of a tube with an aperture-to-length ratio of 1/10, subtending 5°43'30" [7]. The interior of the tube is painted black and sealed with dry air at atmospheric pressure. Solar radiation enters through the crystal-quartz window that filters out the infrared radiation transmitting wavelengths from 280 to 3000 nm. The behavior of the thermopile is similar to the one of a PSP or PIR.

2.2 Summary of the Instruments

Table 2.1 shows a summary of the instruments described before. Column 1 shows the full name of each instrument. Column 2 shows the acronyms used to refer the instrument and column 3 shows the variable that the instrument measures.

Instrument	Acronyms	Measurement
Spectral Precision Pyranometer	PSP	Diffuse and global solar irradiance
Precision Infrared Radiometer	PIR	Hemisperical longwave terrestial or atmospheric radiation
Black and White Pyranometer	B&W	Diffuse solar irradiance
Normal Incident Pyrheliometer	NIP	Normal direct solar irradiance

Table 2.1: Summary of instrument.

2.3 Tools, Facilities, Experiments and Data Set

The present research has been done using data from mainly two data sets:

- Data collected at a radiometric site at the NASA Langley Research Center,
- Data from the Atmospheric Radiation Measurement (ARM) facility in the Southern Great Plains near Ponca City, OK.

2.3.1 Data Collected at NASA LaRC

The experiment at NASA LaRC was conducted from mid September 2000 to mid March 2001. More than six months of continuous global, direct and diffuse solar and downwelling infrared irradiance data were collected. The radiometric facility is located on the roof of building 1250 at the NASA Langley Research Center in Hampton, Virginia, more than 15 m above the ground. The site provides mostly unobstructed view of the downwelling radiative field. The latitude and longitude of the facility are 36.686° and 97.482°, respectively and the altitude 15 m above sea level. Figure 2.6 shows a partial view of the facility. This radiometric site consists of

- Two fix stands with ventilators to measure unshaded downwelling irradiances,
- One Eppley solar tracker with two ventilators to measure shaded irradiances and two locations to attach instruments pointed at the direct solar beam,
- Two data loggers model Campbell Scientific 21X and 23X in a white weather proof enclosure.
- A PC to record data, located on a platform inside the building

Note that the ventilation system of the tracker differs from that of the fix stands. Several instruments have been working in the site

- Five PSP's were used in the facility for different purposes during these six months. Their serial number are
  - PSP 30849 F3
  - PSP 31562 F3
  - PSP 33028 F3
  - PSP 27218 F3
  - PSP 33029 F3

  PSP 31562 F3 and PSP 30849 F3 were used extensively from September 2000 to March 2001 to measure global and diffuse broadband irradiances.
- A pyrgeometer PIR with serial number 30355 was used to measure the downwelling IR irradiance.
- A B&W pyranometer with serial number 32954 was installed in March 2001 for several days substituting the PIR to compare its behavior with the PSP.
- A NIP with serial number 31375 E6 worked during all the experiment measuring normal broadband direct solar irradiance.
- An active cavity radiometer with serial number 31041 was used during calibration activities.

A summary of the positions of the instruments, calibration days and other considerations about the LaRC experiment can be found in Appendix A.

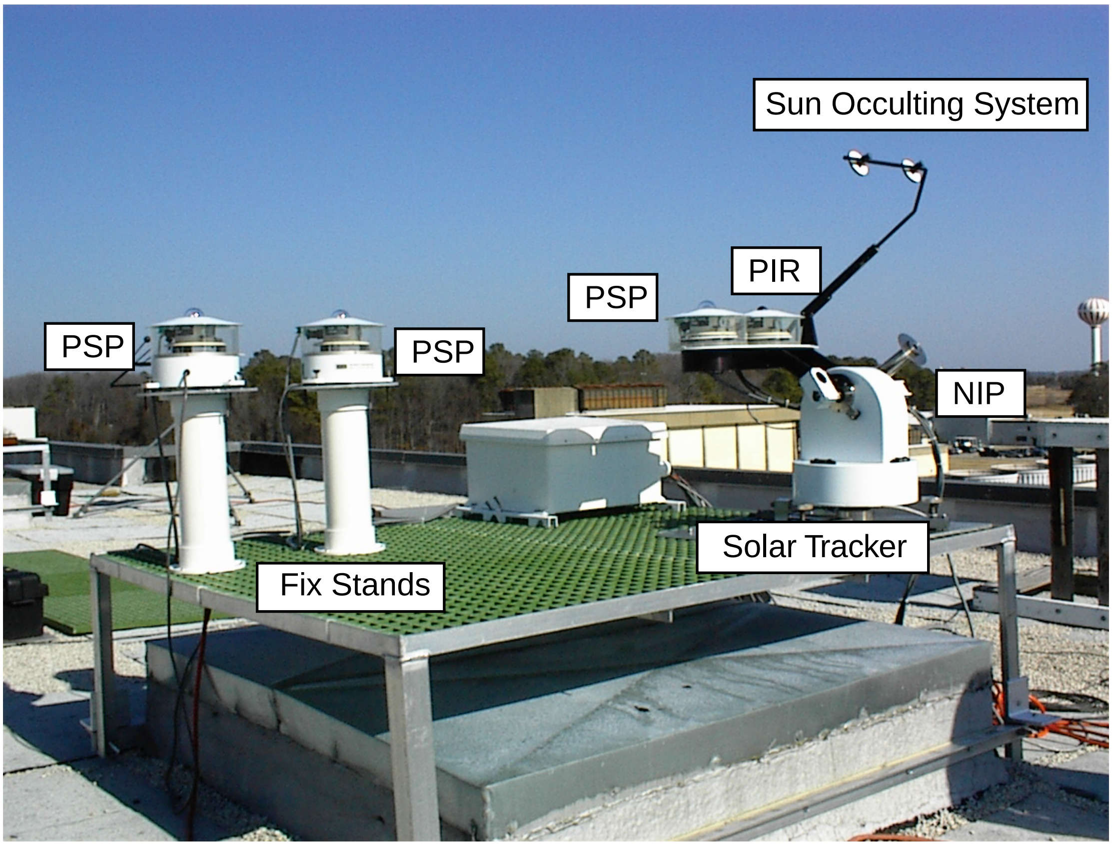

Figure 2.6: Instruments operating at the radiometic site of building 1250 at NASA Langley Research Center, Hampton Virginia

2.3.2 ARM data from the Southern Great Plains Facilities

The main purpose of the ARM program is to study the effect of sunlight and radiant energy on clouds, temperatures, weather and hence on climate [3]. To accomplish this ambitious task the ARM program has three different permanent sites called Cloud and Radiation Testbeds (CARTs) spread out in diverse climate regions. These sites contain facilities where a great variety of instruments take data to be processed later on. These three sites are

- The Southern Great Plains (SGP) located in the U.S. state of Oklahoma, where operations began in 1992,
- The Tropical Western Pacific Ocean (TWP) located in the Pacific islands of Nauru and Manus in the Pacific Ocean close to the Equator where operations began in 1996.
- The North Slope of Alaska (NSA) located in the U.S. state of Alaska where operations began in 1998.

Figure 2.7: Location of the ARM sites. From the ARM web page

These three sites range from tropical to polar latitudes. Figure 2.7 shows the location of the ARM sites. The ARM program is an initiative of the U.S. Department of Energy.

The ARM data used in this study cover a period from July 1999 to March 2001 at SGP. The data set includes diffuse and global broadband irradiances from PSP's, downwelling and upwelling IR irradiances, direct solar irradiances, and also diffuse broadband irradiances from a B&W instrument.

2.4 Instrument Calibration Considerations

Calibration is a very important issue in radiometric measurements. The accuracy of the data depends on a proper calibration of the instrument. PSP's are particularly sensitive instruments. All the PSP's used in this research have been calibrated before and after or during their operational period.

PSP's are calibrated by the manufacturer prior to delivery. The pyranometers are calibrated by Eppley using an integrating hemisphere [8], which is basically a simulation of diffuse radiation from the sky. The integrating sphere produces a diffuse irradiance 700 Wm^{-2} while maintaining the instrument temperature at 25°C. This calibration is used to determine the responsivity in μV/Wm^{-2} of the thermopile of the PSP. Another calibration test is conducted to find out the variation of the responsivity of the instrument with the operational temperature. The cosine response of the instrument, that is, the variation of the responsivity with changing zenith angle of the direct solar beam of the sun (if the PSP is unshaded), must also be characterized. The time response of the thermopile is typically around 1 second. All these parameters are crucial information for the perfect performance of the instrument.

To assure the best possible data the PSP's (especially PSP 31562 F3 and PSP 30849 F3) were calibrated several times during the LaRC experiment to determine the responsivity of the instrument. For the ARM data set the PSP's are calibrated once per year, which is considered to be a reasonable time interval considering the slow rate of degradation of the instruments.

The calibration method recommended by BSRN [23] is the Forgan calibration procedure. The Forgan [11] calibration method requires to use two pyranometers (pyranometer 1 and 2), one of them measuring global solar irradiances and the other diffuse solar irradiances, and a pyrheliometer or an active cavity radiometer measuring direct solar irradiances. The Forgan calibration requires a clear sky day. The two pyranometers are swapped at solar noon, therefore the one that measured diffuse irradiances in the morning will measure global irradiances in the afternoon and vice versa. The three components of solar radiation are related as

$$E_{global} = E_{Direct} \cos\theta + E_{Diffuse}, \tag{2.1}$$

where θ is the solar zenith angle. The irradiance measured by a PSP is the PSP output voltage divided by the responsivity. Equation 2.1 can be rewritten as

$$\frac{V_{A2}(\theta_{0A})}{R_2} = E_{dirA} \cos\theta_{0A} + \frac{V_{A1}(\theta_{0A})}{R_1} \tag{2.2}$$

where V_{A2} is the global irradiance signal from pyranometer 2 and V_{A1} is the diffuse irradiance signal from pyranometer 1 for a particular zenith angle θ_{0A}. A similar equation can be found for the same zenith angle θ_{0A} when the instrument are swapped, that is when pyranometer 1 measures global irradiances and pyranometer 2 measures diffuse irradiances. In each of these pairs of equations there are only two unknowns the responsivities of pyranometer 1 (R_1) and pyranometer 2 (R_2). Solving the two equations yields R_1 and R_2 as a function of θ_0.

To get accurate reponsivities from the Forgan calibration the direct solar irradiance must be measured with a well calibrated instrument. Several calibrations have been conducted at the LaRC site using an active cavity radiometer to measure the direct solar beam.