1.0 BACKGROUND

1.1 Surface Radiation

Meteorologists have utilized recent advances in computer speeds and atmospheric models to create increasingly accurate models of the environment. The computational accuracy of these models for describing the actual physics occurring in the atmosphere is limited by that of the input data. As models progress, this information must also become more accurate, with greater spectral and spatial resolution, in order to correctly characterize the physical atmosphere. Much research is being done on aerosols because of the important role that they play in the earth's atmosphere due to their ability to influence radiation exchange between the earth and space [Eskinazi, 1975]. A current emphasis is to be able to accurately model the effect of aerosols on solar radiation.

Radiative Transfer Models (RTMs) use information about the optical properties of the earth's atmosphere as input to determine a theoretical solar irradiance at the earth's surface. The optical properties are retrieved using methods that include laser and radar measurements of the atmospheric content. If the flux at the earth's surface can be measured exactly, a comparison of the model results and the measured values can be used to validate the methods for retrieving atmospheric optical properties [Haeffelin, 1999]. Major discrepancies exist between models and measurements, which reveals that not enough is understood about the role of aerosols in the optical properties of the earth's atmosphere [Kato et al., 1997]. In order to quantify the discrepancy due to errors in retrieval methods, the uncertainties in the measurement of solar irradiance must be greatly reduced. It is now important to take a close look at uncertainties in solar irradiance measurement and specifically at sources of instrument error in solar radiometers.

Solar irradiance may be measured using either space-based or surface-based instrumentation. Instruments on satellites measure solar radiation reflected by the atmosphere, the clouds, and the earth’s surface. The measurements are compared with established solar irradiances at the top-of-the-atmosphere (TOA) to characterize the transmission through the atmosphere to the earth's surface. This aids in determining the spectral window properties of the atmosphere. Surface instruments measure the radiation incident on the earth's surface and compare it with the solar irradiances in order to determine the effect the atmosphere has had on the radiation. The measurements are compared with the results of theoretical models to verify the atmospheric properties used in RTMs and the property retrieval methods themselves. Surface radiation measurement has the advantage of directly measuring the solar radiation passing through the atmosphere and arriving at the surface, rather than deducing this irradiance from, for example, space-based measurements.

Surface radiation instruments are often employed in networks so that geographical and climatic variations in measurements may be included when accounting for a global radiation budget. The Baseline Surface Radiation Network (BSRN) is a network consisting of approximately twenty stations in climatically diverse regions across the globe [EHTZ, 1999]. Each station has several radiometers to collect data that locally characterize the radiation incident to earth's surface. The World Radiation Monitoring Center is responsible for maintaining a database of these measurements together with collocated TOA measurements. These measurements are used in climate models and satellite calibration algorithms. The Surface Radiation Network (SURFRAD) is a network of six stations across the United States maintained in a similar manner by the National Oceanic and Atmospheric Administration (NOAA) [Cornwall and Augustine, 1999].

1.2 The Pyranometer

The pyranometer is a surface radiation instrument employed in the previously mentioned and other networks. The World Meteorological Organization defines the pyranometer as an instrument used to measure solar radiation arriving from a solid angle of 2π sr (steradians) onto a plane surface in the spectral interval of 0.3 to 3.0 μm [Beaubien et al., 1998]. This name is taken from the Greek words πυρ (pur), meaning fire, ανα (ana), meaning up, and μετρον (metron), meaning measure. Thus the word pyranometer means "measures heat above" [Abbot and Aldrich, 1916]. The Precision Spectral Pyranometer (PSP) model built by Eppley is widely used for monitoring shortwave radiation from the sun and sky incident to the earth's surface. Figure 1.1 presents the major components of the pyranometer.

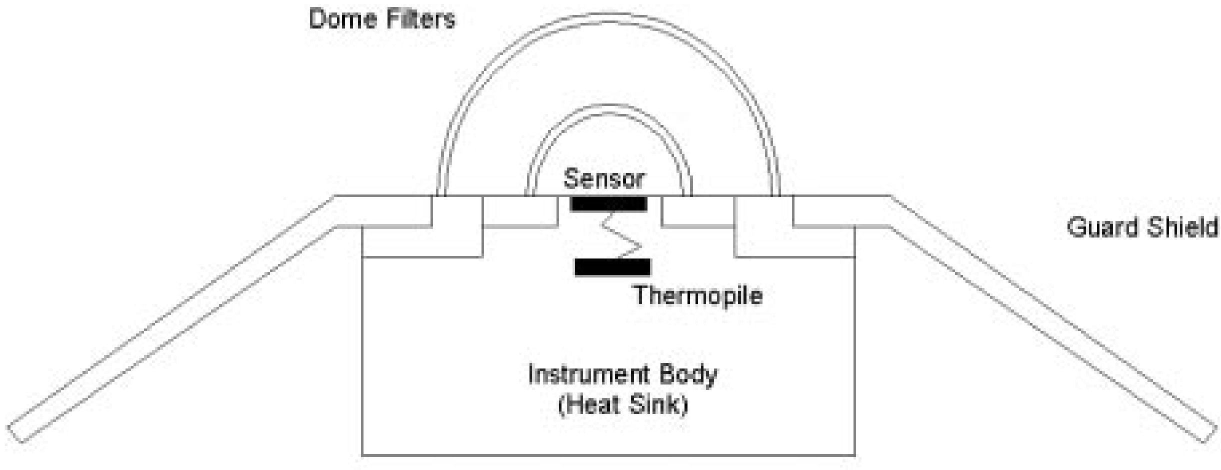

Figure 1.1 The pyranometer

The pyranometer is a thermopile-based radiometer. The sensor is a blackened disk mounted in close thermal contact with the hot junction of a thermopile. The cold junction is in intimate thermal contact with a heat sink consisting of the high thermal capacity brass instrument body. In the pyranometer, radiation arrives at the surface of the sensor after being filtered through two hemispherical domes. These domes are precision ground and polished hemispheres of Schott optical filter glass. They block transmission of infrared radiation and allow only shortwave radiation to reach the sensor. The WG7 filter in use for shortwave measurements in the Eppley PSP is transparent from 0.285 to 2.8. The filter function for the 2.0-mm Schott optical filter glass dome is shown in Figure 1.2 as provided by Eppley Laboratory. The domes may be replaced by filters that allow only transmission of radiation pertaining to a specific spectral band of interest.

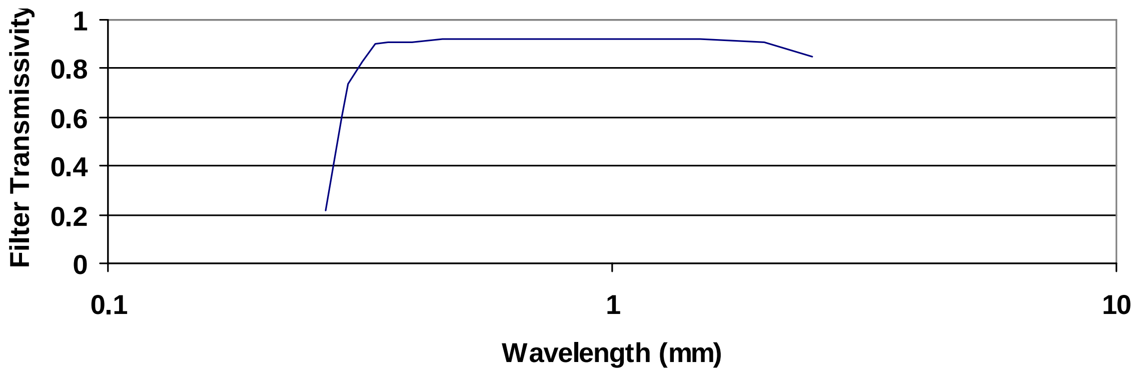

Figure 1.2 Filter function for Schott glass 2.0-mm dome filter

The radiation absorbed by the sensor result in a temperature rise. The temperature difference between the junctions of the thermopile results in a voltage signal, which is measured and interpreted in terms of the spectral flux [Weckman, 1997].

The thermopile of the pyranometer consists of m junctions between two dissimilar metals that together create a signal m times that produced by a single thermocouple formed by the same two metals. The Eppley PSP uses a circular multi-junction copper-constantan plated, wire-wound type thermopile. The temperature dependence that generates a non-linearity of the thermopile response is compensated by circuitry built into the instrument. Eppley claims the temperature dependence of the instrument does not vary more than one percent from its operation at 20°C when being operated in conditions between –20°C and +40°C.

The sensor surface of the Eppley PSP is coated with Parsons' black lacquer, which is a wavelength-independent absorber. The surface is roughened to maximize its blackbody behavior, bringing the apparent emissivity as close to unity as practical. For modeling the performance of the instrument, all incident radiation is assumed to be absorbed by the sensor surface. It is important to note that the sensor absorbs radiation equally well at a wide range of wavelengths, though the instrument is intended to measure only shortwave radiative fluxes. Though the filter domes block direct longwave radiation from reaching the sensor surface, the sensor may still be affected by thermal radiation from its immediate surroundings, such as from the inside of the inner dome and the annular surface surrounding the sensor.

Measurements of radiative components are typically taken on rooftops or far from buildings and other obstructions in order to increase the instrument's view of the sky. The pyranometer may be operated to measure either global or diffuse shortwave radiation. Global radiation is all radiation received by the instrument in the wavelength interval of interest; it is measured by leaving the instrument exposed to all downwelling radiation. Global radiation consists of both direct and diffuse components of solar radiation. The direct component is received only from the direction of the sun-earth vector, while the diffuse component is received from the entire hemisphere above the instrument. The direct component is solar radiation transmitted through the atmosphere without scattering as well as that scattered in the forward direction. The diffuse component is solar radiation scattered by molecules and particles in the atmosphere. The measurement of the instrument is governed by the cosine law; i.e. a lesser area intercepts the flux as the incident angle deviates from the zenith, as shown in Figure 1.3. Diffuse radiation is differentiated from the global by incorporating a shading device. The shading device, which may be automated by pairing it with a solar tracker that follows the sun as it moves across the sky, must block radiation from the solar disk from direct incidence on the instrument while minimizing the total shading on the instrument since any shade will remove diffuse radiation from the measurement. Many networks employ both a shaded and an unshaded PSP in addition to a normal-incidence pyrheliometer. This latter measures the shortwave flux in the direct solar beam through the plane perpendicular to the radiation. Measurement consistency can then be verified by comparing the sum of the direct multiplied by the cosine of the solar zenith angle and the diffuse measurements with the global measurement.

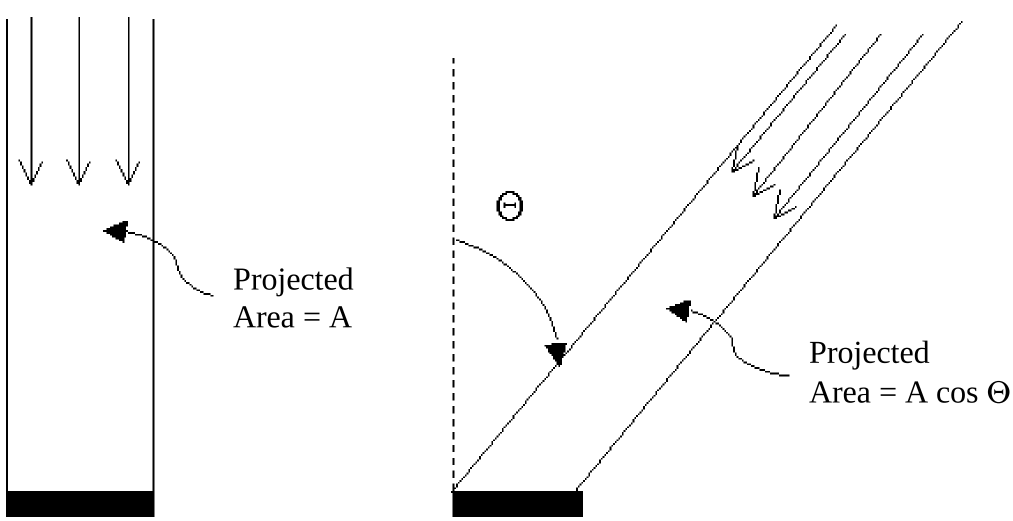

Figure 1.3 Cosine-law response of the sensor surface

1.3 Uncertainty in Pyranometer Measurement

As with all instrumentation, it is important to quantify the extent of uncertainty in measurements obtained with the pyranometer. The significance of instrument accuracy in diffuse measurements becomes apparent once the magnitudes of these irradiances are considered. Though also present in global measurements, the fractional error is not as significant in this case. Three main factors contribute to the instrument uncertainty: instrument calibration, instrument sensitivity to its operating conditions, and thermal exchanges within the instrument [Haeffelin et al., 1999].

The smaller magnitude of the diffuse radiation measurements compared to global measurements indicates that diffuse measurements are more sensitive to instrument uncertainty. Global shortwave irradiances typically fall around 800 W/m^2 at noon on a clear day in Hampton, VA, while the corresponding diffuse component of radiation will typically be only 150 W/m^2 [Kato, 1999]. The effect of a constant offset of 10 W/m^2 results in a seven-percent error in diffuse measurements, and only a one-percent error in direct measurements.

Instrument uncertainty directly concerns those who use the measurements to verify their models. In a comparison performed between data obtained during the 1995 Atmospheric Radiation Enhanced Shortwave Experiment (ARESE) and two radiative transfer models for clear-sky radiation, the models appeared to overestimate downwelling shortwave irradiance at the surface of the earth [Kato et al., 1997]. The discrepancies were apparent in the diffuse irradiances, which cannot be explained by variations of aerosol optical properties in a realistic range. However, in order for the models to reproduce measurement values, not only must they accurately portray physics, but also the instruments must accurately interpret irradiances.

The immediate source of instrument uncertainty is an absolute calibration of the instrument, which must be current. The instruments in radiation networks are typically calibrated with a primary standard instrument at least once per year. The calibration results in an instrument sensitivity to a known radiation source in volts per watt per meter squared. This sensitivity is derived from the behavior of the instrument in a controlled environment where the instrument body and filter domes are maintained at a constant temperature. The calibration constants may be different when the instrument is used outside the laboratory.

The Eppley pyranometer has been shown to be sensitive to parameters of its operating conditions. Variations in the filter properties and the absorption abilities of the sensor surface may exist that cause the instrument response to vary from the cosine response shown in Figure 1.3. This makes the pyranometer sensitive to the location of the sun in the sky and to the orientation of the pyranometer itself. Readings may also be affected by the proximity of buildings, ventilation units, or other significant sources of radiation. In addition, ambient temperature affects the operation of electronic components, such as the thermopile, though this latter offset is minimized by compensating circuitry. The operating conditions that may affect measurements should be frequently monitored and compensated for.

A third source of uncertainty in this instrument is thermal irradiance on the surface of the instrument sensor. The signal is essentially a direct function of the temperature difference between the sensor surface and the heat sink. Therefore, any flux incident on the sensor surface that does not affect the heat sink is included in the measurement. These include, but are not limited to the following: thermal radiation exchange with the filter dome and floor of the filter dome surrounding the sensor, convective and conductive heat fluxes in the air within the inner dome, and conductive or radiative heat fluxes to the body of the instrument and possibly through the thermopile itself.

1.4 Zero Offset Signal

The offset due to thermal exchanges is often referred to as a zero offset because it becomes apparent at times when the signal should be zero. At night, the solar irradiance is zero so that any signal output from the instrument is fictive. Often, when exposed to the nighttime sky, the Eppley PSP produces a negative signal. This seems to indicate a net radiative exchange to the inner filter dome from the sensor. During the night, if exposed to a clear nighttime sky, the instrument will radiate to the sky as an effective sink with a temperature of 220 K [Kato, 1999]. The largest effect is imposed on the outer dome because it has a large area in radiative exchange with the sky and a small thermal mass with which to resist cooling. The effect is much less noticeable on the instrument body because it is more massive and is shielded from the sky by a specularly reflective shield. The radiative exchange creates a gradient on the outer dome that lowers its temperature below that of the instrument body. The inner dome, in turn, is exposed to the outer dome, with the result that its temperature is lowered as well. The sensor surface is then exposed to the inner dome at a lower temperature than that of the sensor surface, thereby creating a net flux from the surface. This flux will result in a negative signal and an apparent negative flux measurement.

It has been shown that ventilation decreases the zero offset by using the air to maintain a more uniform temperature over the surface of the instrument [Drummond et al., 1965]. Cloud cover during the night also decreases the offset by raising the effective sky temperature to the effective radiative temperature of the clouds, which can be near the ambient surface air temperature.

1.5 Current Methods of Correction

Various techniques have been employed at monitoring stations in an attempt to correct for the zero offset. Alberta and Charlock with the Baseline Surface Radiation Network (BSRN) have made note of a nighttime difference between the standard up-looking pyranometer and a down-looking pyranometer that views the earth's surface [Alberta, 1999]. The up-looking, or sky-viewing, instrument gives a negative voltage signal while the down-looking, or earth-viewing instrument maintains a zero signal. The CAGEX (CERES/ARM/GEWEX) group has determined a correction algorithm for the diffuse measurement. The algorithm uses an empirical relationship between the thermopile output of a pyrgeometer, which is sensitive to downwelling longwave radiation, and the nighttime output of the PSP. The pyrgeometer output is then used to compute the zero offset signal of a PSP used to measure diffuse solar radiation. The empirical relationship has a constant linear slope based on daily or weekly data. The relationship will not always correct shortwave measurements taken at night to zero, and the results have not been validated.

1.6 State of Compensation Research to Date

Several modifications to the pyranometer have been proposed in order to compensate for the offset problem. One of these modifications involves modifying the sensor optical properties by including both black and white sections. Each section is exposed to the same conductive and radiative conditions, except that the black section will absorb most radiation in the shortwave, whereas the white section will reflect most of it. The variation in absorption of radiation can be used to remove the longwave influence on the shortwave signal. Other modifications are aimed at reducing thermal effects by subjecting the instrument to strong ventilation in order to reduce or eliminate the temperature gradient. This solution has two major drawbacks. First, the power needed to drive the ventilating device itself becomes a heat source for the convecting fluid. In addition, since heat transfer via convection is a function of the difference between surface and air temperature, the smaller the gradient on the instrument, the harder it is to reduce the gradient. A daytime experiment by Drummond and Roche in 1965 showed that a ten-percent overestimated flux was reduced to only a three-percent overestimation using 10-m/s ventilation. The remaining discrepancy was attributed to an inability to remove absorbed radiation using convection [Drummond et al., 1965].

Various studies have been performed on monitoring the instrument's thermal state during operation and using this information to correct data. A 1998 study by Bush et al. advocates using a measured dome temperature and a correction algorithm that is linear with the difference between the dome temperature to the fourth power and the instrument body temperature to the fourth power.

A study is currently being performed by a team at NASA Langley headed by Dr. Martial P. Haeffelin to quantify temperature gradients within the instrument. The effects of these gradients are then examined to determine how they affect the operation of the instrument and specifically, how they influence the thermopile signal. The end goal of this effort is a better understanding of thermal radiation exchanges within this and other radiometers, and possible calibration algorithms for various environmental conditions, for both daytime and nighttime offsets. The team proposes that a small modification to the existing instrument involving continuous monitoring of a single representative dome temperature will be sufficient for correcting calibration, including the thermal effects of the dome gradient.

1.7 Objectives for Investigation

The objective of this research is to determine the utility and the accuracy of a finite element model in calibrating the pyranometer. In this endeavor, several steps are taken in model construction and validation. An initial look at the instrument includes an examination of existing analytical models that describe the physics of the instrument. This concludes with a verification of what information is necessary for a measurement correction algorithm.

A numerical model simulates the thermal behavior of the outer dome of the instrument, the part of the instrument that is most affected by varying external conditions. The conditions that produce the zero offset are re-created in the model to produce the resulting dome temperature gradient. A parametric study is performed to show the effect of increased convection on reducing the dome gradient.

The results of the model are verified using simple, well-controlled experiments. The outer dome is placed under transient warming and cooling conditions, while the temperature of the dome at critical locations is monitored by thermistors. The corresponding temperatures in the numerical model are then compared with the experimental results.

The effort to characterize the thermal exchanges within the pyranometer is important in order to understand how these exchanges affect instrument measurements. A finite element model of the entire instrument will be a useful tool in providing insight into these exchanges with precision and detail. The effort detailed in this thesis has been a significant contribution to this ultimate goal.

It is clear that a better understanding of the instrument's thermal behavior is necessary to determine a correction protocol for measurements. Chapter 2 details the analysis of the radiative exchange processes within the instrument.