Characterization of Radiation Exchange within the Eppley Pyranometer

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Introduction

The Eppley Precision Spectral Pyranometer (PSP) is used to measure broadband shortwave irradiances on the earth's surface. Instrument measurements have been shown to be influenced by infrared radiation that produces an offset from the signal as a result of incident shortwave radiation. Currently, the effort is to model the energy exchanges within the instrument, so the measurement error can be described as a function of external conditions (Haeffelin et al. 2001).

A numerical model of the thermal exchanges within the instrument consists of two modules. A finite element method (FEM) analysis simulates heat diffusion in the instrument and a Monte Carlo ray-trace (MCRT) code models radiative exchanges in the instrument.

The FEM analysis had previously been used to model heat diffusion in the outer dome of the instrument. This model produces the dome temperature distributions resulting from specified external boundary conditions.

Temperature gradients in the instrument create radiative exchanges between the domes and the sensor surface, and results in a measurement error. An MCRT code is used in the current effort to model the influence of these radiative exchanges on the sensor signal. The code has the capability of reproducing realistic operating conditions in order to confirm the offset to be expected from a variety of ambient conditions. Wind speed and air temperatures, ambient conditions affecting the temperature distribution, may be varied in this model.

The goal of the effort is to create an MCRT model of the pyranometer for integration with the results of the existing FEM model. With the completed tool, an accurate study of the signal sensitivity to various external conditions, such as wind and air temperature, may be conducted.

Monte Carlo Ray-Trace Analysis

The MCRT method is a statistical approach that simulates thermal radiation exchange processes inside an enclosure. Energy bundles are emitted from source surfaces. The surface and volume properties of absorptivity, reflectivity, specularity, and transmissivity are treated as probabilities. When a bundle encounters a surface, a decision is made as to the fate of the bundle, i.e., whether it is absorbed, reflected, or transmitted. The life history of each bundle is traced until the bundle is absorbed.

The MCRT method is used to estimate the distribution factor. The distribution factor D_{ij} is defined as the fraction of energy that is emitted from surface element i with a specified directional distribution and absorbed by surface element j. The coefficients D_{ij} are estimated as

$$D_{ij} \cong \frac{N_{ij}}{N_i} \qquad (1)$$

where N_{ij} is the number of rays emitted by surface element i absorbed by surface element j, and N_i is the total number of rays emitted by surface element i. The sum of the distribution factors from surface element i to all possible surfaces in the enclosure must be equal to unity, or

$$\sum_{i=1}^{n} D_{ij} = 1 \qquad (2)$$

That is, energy is conserved. Once the distribution factors are found for a given geometry, the heat transfer from element i to element j can be estimated as

$$Q_{ij} = \varepsilon_i A_i \sigma T_i^4 D_{ij} (W) \qquad (3)$$

where ε_i is the total emissivity of surface i, A_i is its area (m^2), σ is the Stefan-Boltzmann constant (5.6696×10^{-8} W/m^2-K^4), and T_i is the temperature (K) of surface element i. The size of the surface elements into which the enclosure is subdivided depends on the desired spatial resolution and accuracy.

The reciprocity principle for distribution factors reduces the computational analysis. The radiation exchanges of interest are those concerning the sensor surface. The reciprocity principle is derived from the first law and relates the distribution factor from surface i to surface j with that from surface j to surface i according to

$$\varepsilon_i A_i D_{ij} = \varepsilon_j A_j D_{ji} \qquad (4)$$

With the reciprocity principle, energy bundles may be emitted from the sensor surface and the resulting distribution factors will identify the significant thermal sources throughout the instrument. Examples of some significant radiative exchanges are shown in Figure 1.

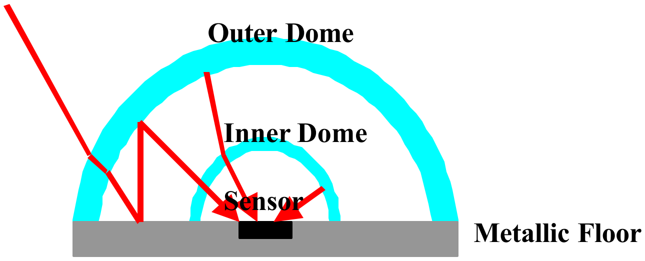

Figure 1. Monte Carlo ray-trace model of pyranometer.

Flux at Sensor Surface

The flux at the sensor surface is a combination of shortwave and longwave radiation. The shortwave radiation originates outside the instrument from direct or diffuse solar radiation. Solar radiation is attenuated by the atmosphere, and further attenuated by the filter domes before reaching the sensor surface. The intention of the measurement is to quantify this radiation. Longwave radiation originates within the instrument itself. Temperature gradients throughout the domes create thermal radiation exchanges with the sensor surface. The existence of a local surface temperature different from that of the sensor creates a local thermal radiation exchange with the sensor surface.

The offset due to local thermal radiation exchange is determined by several parameters. The actual temperature of the dome at a given location will affect the offset due to the local radiation source. The greater the difference between the local temperature and the sensor surface temperature, the greater the influence on the instrument signal. The other parameters include surface properties and transmissivity of the domes. These parameters are integrated together in the distribution factor. The distribution factors for the Eppley pyranometer include the infrared surface properties given in Table 1.

Table 1. Surface properties for the Eppley pyranometer.

Surface	Emissivity	Transmissivity	Reflectivity	Specularity
Outer Dome	0.9	0.01	0.09	0.5
Inner Dome	0.8	0.11	0.09	0.5
Metallic Floor	0.0	0.0	1.0	1.0
Sensor	1.0	0.0	0.0	0.0

The distribution factors obtained with the MCRT analysis are shown in Figure 2.

The FEM analysis was performed on a pyranometer dome exposed to the nighttime sky where the ambient temperature is 0°C and the effective sky temperature is -53°C. The magnitude of the resulting temperature gradients for various convective conditions is shown in Figure 3 (Smith et al. 1999).

It is assumed the inner dome temperature gradient is a scale factor of the outer dome temperature gradient produced by a given set of external conditions. The scale factor used in the current example is one-fourth. The distribution factors obtained with the MCRT analysis are used with the temperature gradients obtained with the FEM analysis in Eqs. (2) and (3) to calculate the heat flux arriving at the sensor surface. The amount of flux above, that arriving from a uniform dome at the sensor temperature, represents the offset and is shown in Figure 4.

The results of the model for this example are consistent with observed nighttime pyranometer measurements.

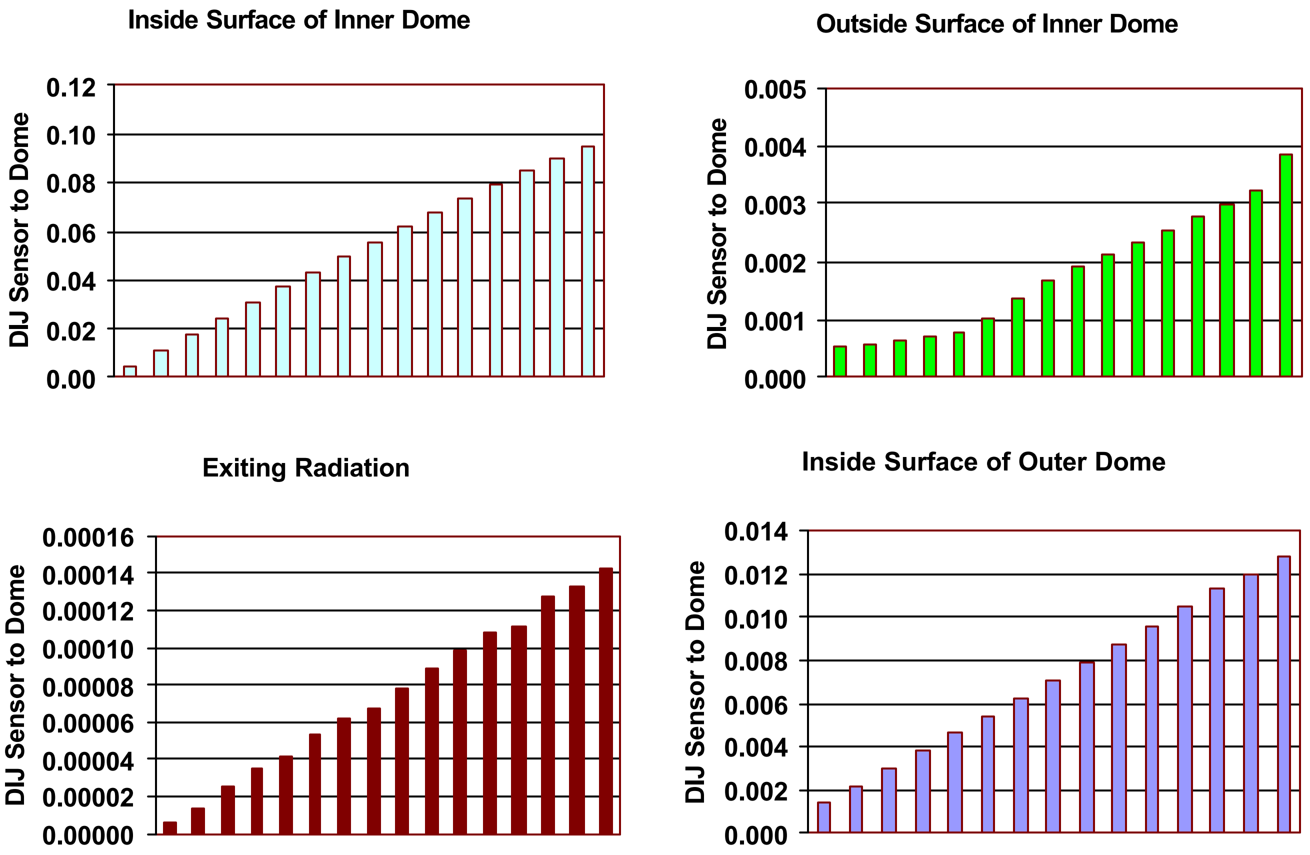

Figure 2. Distribution factors for constant areas of various thermal sources in the instrument.

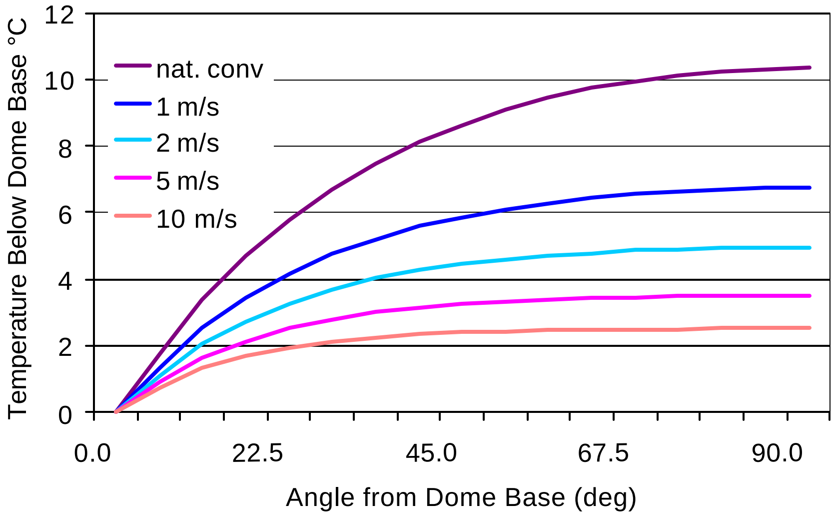

Figure 3. Gradients on outer dome from base to tip resulting from various convective conditions.

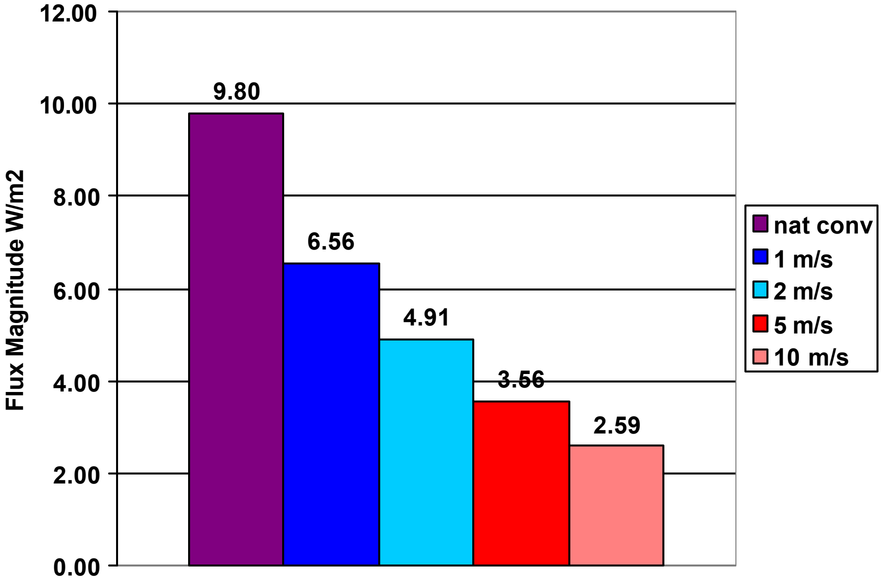

Figure 4. Expected net flux resulting from various convective conditions at night.

Conclusions and Further Work

The characterization of thermal exchanges within the pyranometer is important to know in order to understand how these exchanges affect measurement accuracy. With such understanding, instruments may be suitably modified to be able to provide necessary information for data correction. A numerical model is a useful tool in providing insight into these exchanges. The effort described here represents the advancement for the model of the Eppley pyranometer.

A few enhancements are under consideration for the model of the Eppley pyranometer. The FEM conduction model will be enhanced to produce more exact solutions for thermal behavior. The MCRT radiation model will be utilized to describe directional characteristics of the instrument response. The combined model will be expanded to include absorption of solar radiation in the domes, and includes both radiative and conductive analysis.

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References

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