Optical Properties of a Plastic Pyranometer Head

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ABSTRACT

The optical characteristics of a newly designed two-step pyranometer head are described. The head is suitable for use in the spectral range 400–720 nm. It is characterized by a cosine error which is less than 1.5% over the angular range 0–85° and has a differential polarization cosine error no greater than 3.0% in that same angular interval.

1. Introduction

Spectral pyranometers are employed to measure the spectral distribution of the normal component of the global radiation incident on a surface. In many meteorological applications, the instrument is used to determine the downwelling irradiance at the surface of the earth over the visible portion of the solar spectrum. The incident radiation in this application originates from all portions of the sky and generally contains a significant fraction of polarized radiation. The purpose of this note is to characterize a newly designed pyranometer head in terms of its ability to measure this radiation.

2. Pyranometer cosine error

The response of an ideal pyranometer is proportional to the component of the incident flux normal to the plane of the pyranometer head. This response should vary as the cosine of the angle of incidence of the impinging flux. The deviation in response of a real pyranometer from the cosine function is termed the cosine error. If $R(\theta)$ is the response of the pyranometer to flux incident at the angle θ with respect to the normal of the pyranometer surface, then the percent cosine error can be written as

$$C_{\parallel,\perp}(\theta) = 100\left[\frac{R_{\parallel,\perp}(\theta)}{R_{\parallel,\perp}(0)}\left(\frac{1}{\cos\theta}\right) - 1\right]. \quad (1)$$

Both the cosine error $C(\theta)$ and the pyranometer response $R(\theta)$ are subscripted to indicate that the performance of the instrument is dependent upon the polarization of the incident radiation. $C_{\parallel,\perp}(\theta)$ and $R_{\parallel,\perp}(\theta)$ refer to the performance of the pyranometer when the electrical field of the incident radiation is either parallel or perpendicular to the plane of incidence. This sensitivity is generally not stated in published performance specifications for pyranometers. As will be seen, the cosine error curves can vary substantially for differing components of polarized light. Here the term averaged cosine error, equal to $(C_\parallel + C_\perp)/2$, will be used to describe the cosine error of the pyranometer head when it is illuminated with unpolarized light.

The cosine error of the pyranometer head was measured in these studies by mounting the head and its associated detector on a rotary table. The head was illuminated by a regulated 1000 W tungsten halogen cycle lamp with an aperture of 1.5 cm. The distance between the head and the light source was 2 m. Provision was made for the positioning of optical filters and linear polarizers in the optical path, according to the requirements of the particular experiment. All exposed surfaces were covered with a black velvet cloth, and the optical volume was baffled to prevent stray radiation from reaching the pyranometer surface.

3. Characteristics of the basic pyranometer head

The basic pyranometer head used in this study is shown in Fig. 1. The head was machined from white translucent acrylic plastic (Rohm and Haas W-2447) in the form of a cylinder and was then cemented into a corresponding opening in the center of a black opaque plastic disc (Polycast 2025) 5 cm in diameter and 0.64 cm in thickness. Such plastics have been previously used in instruments such as these and have been found to be stable with respect to changes in mechanical and optical properties (Kerr, *et al.*, 1967; Stimson, 1974; and Huttenhow, 1976).

Cosine error curves for the basic head are shown in Fig. 1. These curves are valid over the spectral range 400–720 nm. The error bars represent the probable error associated with the measurements. These curves demonstrate that the basic head se-

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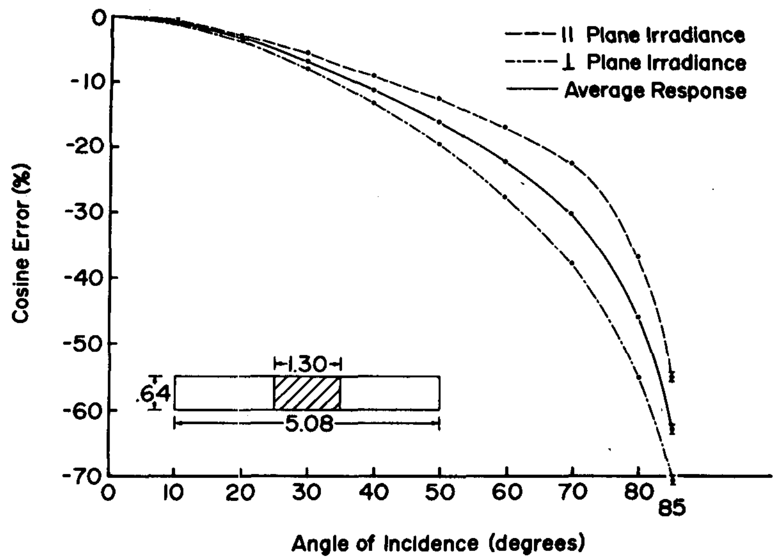

FIG. 1. Cosine error of a smooth, level head to polarized light. Head dimensions are given in centimeters.

verely underestimates the normal flux component for angles of incidence > 20°. They also show that the response of this head is significantly dependent upon the state of polarization of the incident flux. For example, at an angle of incidence of 70°, the cosine errors for the two states of polarization differ by 14%.

The primary cause of the differential polarization response can be attributed to the optically smooth surface of this head. The polarization-dependent transmissivity of such a surface is discussed in standard optical texts (e.g., Jenkins and White, 1957). In order to minimize the polarization error, it is necessary to roughen the surface so that specular reflectance is avoided. This was done by mounting the head in a rotating fixture and then sandblasting it with silicon carbide powder (320 mesh). The cosine error curves for a roughened head are shown in Fig. 2. It can be seen that this process removes the major portion of the polarization error. The differential polarization error at an angle of 70° has now been reduced from 14% to 3%.

The spectral transmissivity of the basic head was measured utilizing a 0.25 m grating spectrometer at a resolution of 2 nm. Since the flux transmitted by

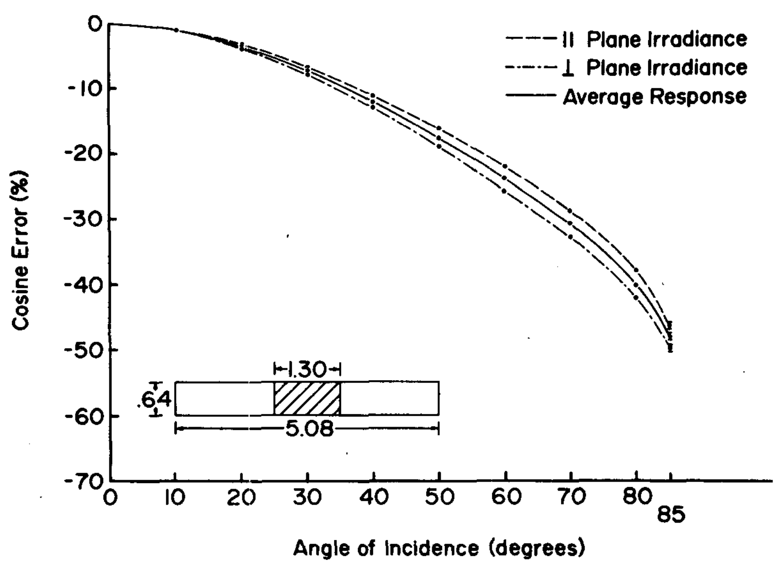

FIG. 2. Cosine error of a sandblasted level head to polarized light. Head dimensions are given in centimeters.

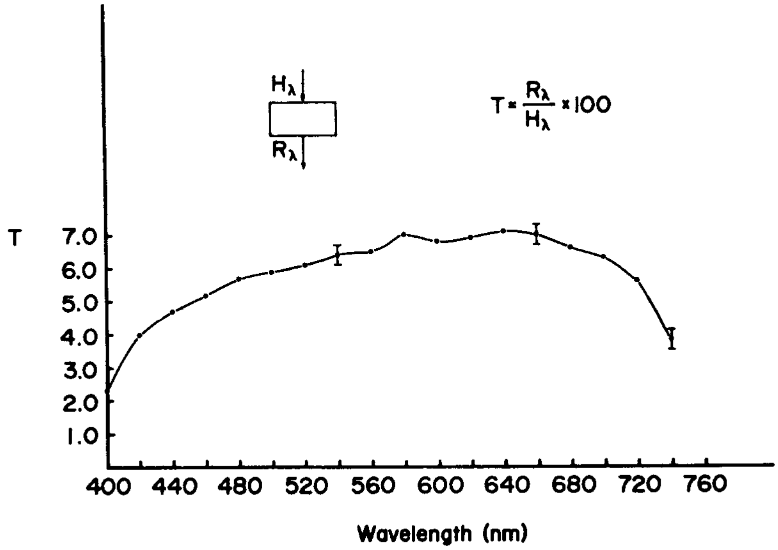

FIG. 3. Spectral characteristic of plastic W-2447, reported as the ratio times 100 of the normal radiance leaving the bottom surface of the head to the irradiance normally incident on the top surface.

the head is diffuse and the incident flux is collimated, the transmissivity is reported as the ratio of the normal radiance leaving the lower surface of the head to the irradiance normally incident on the upper surface. The results of these measurements are given in Fig. 3. The useful spectral range of this head is from 400 to 720 nm.

4. Characteristics of a one-step cosine error correction surface

The method used in this study for the correction of the large cosine error which appears at zenith angles > 20° was first employed by Pleijel (1944) and extended by Pleijel and Longmore (1952). Here, the translucent cylinder is allowed to project above the surrounding surface, so that the side area of the raised portion of the cylinder is increasingly exposed to the incident light with the increase in the angle of incidence. The correction to the cosine error of the basic head provided by this approach is given approximately as

$$\Delta = 100 \frac{2h}{\pi r} \tan\theta, \tag{2}$$

where h represents the exposed height and r the radius of the cylinder. The cosine error for the case h

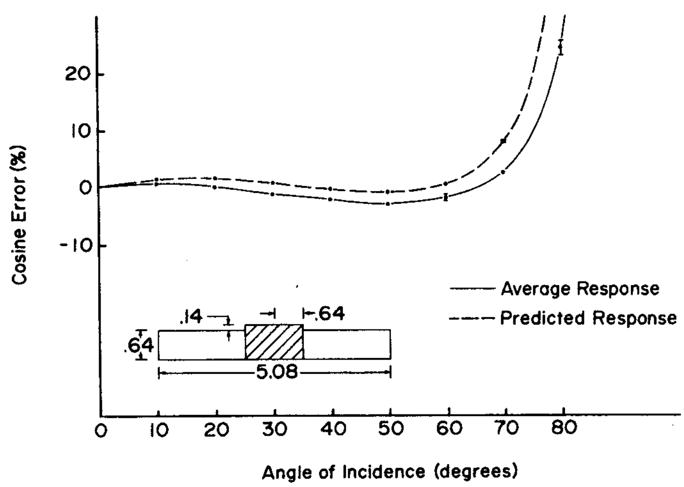

FIG. 4. Measured and predicted cosine error of a sandblasted elevated head to polarized light. Head dimensions are given in centimeters.

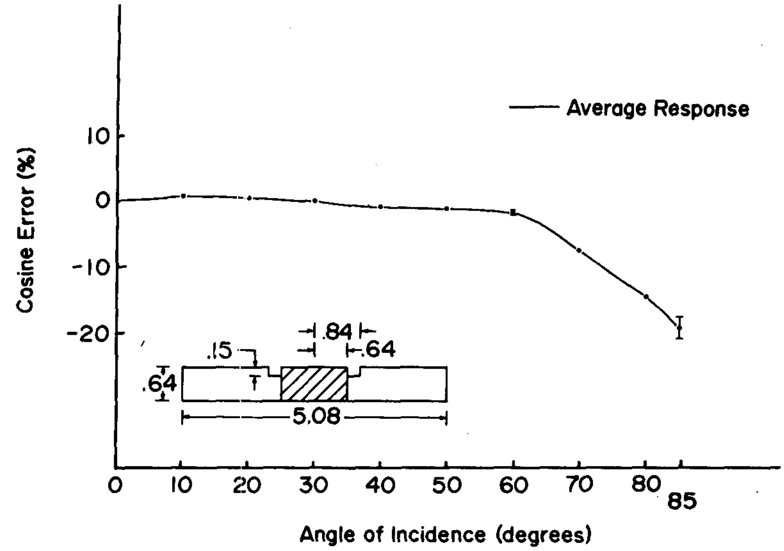

FIG. 5. Cosine error of a sandblasted single-step head to polarized light. Head dimensions are given in centimeters.

= 0.14 cm and r = 0.64 cm is given in Fig. 4. The solid line in this figure represents measured data, and the dotted line gives the predicted cosine error based upon Eq. (2) and the cosine error of the basic head.

It is evident from Fig. 4 that the cosine error has been substantially reduced when compared to the basic head. However, it should be noted that the error increases significantly with angle after 70° and becomes infinite at 90°. This large error occurs because the side of the cylinder remains exposed to the incident flux at 90°. Pleijel and Longmore (1952) corrected this error by surrounding the exposed portion of the cylinder with a concentric ring which blocks the incident radiation at an angle of 90°. The optimum position of this ring was determined empirically by previous investigators. An attempt was made to analytically specify the ring location, but this approach proved unsuccessful because of the difficulty in defining the optical properties of the cavity formed by the cylinder and occulting ring.

The ring location in this study was determined experimentally. As an example, the cosine error for a head configuration in which occultation began at 55° and was complete at 90° is given in Fig. 5. It

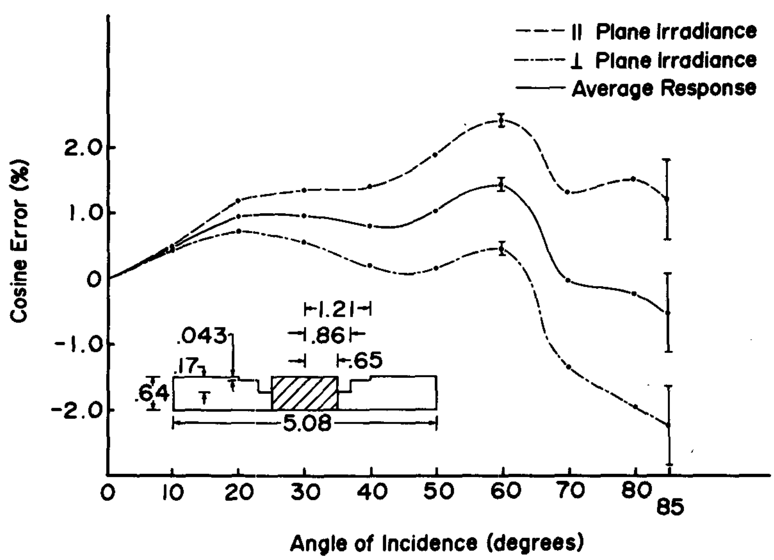

FIG. 6. Cosine error of a sandblasted double-step head to polarized light. Head dimensions are given in centimeters.

can be seen that the cosine error is less than −2% in angular range 0–65° and then increased to −19% at 85°. Additional experiments were undertaken in which the ring was positioned such that occultation began at angles in the range 55–80°. These experiments were not successful, in that the cosine error exceeded |4%| at some point in each of the tests.

5. Characteristics of a two-step correction surface

In order to increase the accuracy of the cosine response of the pyranometer, consideration was given to a more complex occulting surface. In principle, a zero-error pyranometer can be constructed by forming an occulting surface with such geometry that the lateral portion of the exposed cylinder is just that amount required to give zero error at all angles. The generation of such a surface presents a fabrication problem. Consequently, it was decided to approximate this surface by two steps, as suggested by Huttenhow (1976).

As the initial stage in establishing the geometry of a two-step occulting surface, an approximate zero-error continuous surface was generated based upon Eq. (1). This was done by determining the exposed height h of the cylinder required to give zero cosine error as a function of flux zenith angle. As a first cut, a two-step surface was constructed in which the first step was based upon the surface shown in Fig. 4 and the second step was specified by the requirement that zero error exist at 80°. Although this surface provided considerable cosine error improvement over the basic head, some 30 variations in this surface were investigated before the final surface shown in Fig. 6 was established. The cosine response for this head lies within 1.5% of the true cosine curve. The differential polarization error is less than 2% over the angular range 0–65° and increases to 3% at 85°.

6. Pyranometer head longevity

A pyranometer head of the type shown in Fig. 6 was continuously exposed to the weather elements for a period of 13 months. The test location was the roof of the Physics-Atmospheric Sciences Building at The University of Arizona. Measurements were made of the cosine response of the head at various times during this test period. The head was brushed clean prior to each measurement. The cosine error remained within 1% of the initial value after a period of four months which covered the summer of 1980. Subsequent measurements, made at four-month intervals, indicated a progressive positive increase in cosine error at an average rate of 0.25% per month. During the test exposure, the head was scoured a number of times by dust storms, with the result that the edges of the steps became somewhat rounded. This allowed additional flux to impinge on the sides of the cylinder, increasing the cosine error. The normal transmission was not substantially changed during this test period.

7. Summary

This note describes the development of a two-step plastic pyranometer head useful in the spectral range 400–720 nm. The cosine error for the head is less than 1.5% over angular range 0–85°, and the differential polarization cosine error is less than 3% over this same angular interval. The head has been continuously exposed to the weather for a period of 13 months. The maximum cosine error at the end of this period was 4.8%.

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