Investigations in Pyranometer Design

D. J. BEAUBIEN, A. BISBERG, AND A. F. BEAUBIEN

Yankee Environmental Systems, Inc., Turners Falls, Massachusetts

(Manuscript received 13 January 1997, in final form 30 July 1997)

ABSTRACT

Three approaches to the design of total (global) solar pyranometers that employ new technologies and materials of manufacture are described. The pyranometers are designed to meet or exceed the requirements for high quality instruments as classified by the World Meteorological Organization's *Guide to Meteorological Instruments and Methods of Observation.* A pyranometer employing linear thin-film platinum resistance thermometers to measure the temperature rise of an optically black metal surface is presented; a second design utilizes a bismuth telluride thermopile to measure the temperature rise of an optically black silver disc, and a third design uses an optically black, fast-response thin film bismuth antimony thermopile with diffusing foreoptic for determining the solar irradiance level. All three designs employ optically black radiation receiving surfaces. The structure of the radiation detection schemes are presented and electronic circuitry, when required, is described. For each of the instrument types, the measured time responses, ambient temperature response, cosine response, and azimuth asymmetry response are presented. Special-purpose apparatus used for determining cosine response and azimuth response is presented in the appendix.

1. Introduction

A standard instrument for measuring the combined direct and diffuse components of the solar irradiance is the global solar pyranometer. The World Meteorological Organization (WMO) describes the pyranometer as an instrument "for measuring solar radiation from a solid angle of 2π steradians into a plane surface and (with) a spectral range of 0.3 to 3.0 μm" (WMO 1997). Pyranometers are widely used by meteorologists, climatologists, atmospheric scientists, and renewable energy researchers.

Pyranometers suitable for solar energy measurements fall into one of two categories: those that measure the temperature rise of a black surface referenced against a thermal mass or a reflective white surface, and those that convert radiant energy directly to electrical energy, that is, photometric types. The black surface pyranometers typically offer spectrally uniform response from 300 to 3000 nm and some meet or exceed the WMO specifications suggested for high quality instruments suitable for use as secondary standard measurements. The photometric types, although less expensive to manufacture, have spectral responses governed by the semiconductor material, typically silicon, and are not classified by the WMO for reference-grade applications (Frohlich 1986). Photometric pyranometers are not treated in this paper.

This paper examines three types of black surface thermal-converting pyranometers: two designs employ conventional double-domed enclosures and a third uses a diffusing foreoptic. Three types of temperature measurement are examined; platinum resistance thermometers (PRTs), a bismuth telluride thermopile, and a thin film bismuth antimonide thermopile. Each design offers specific advantages and drawbacks.

The PRT version offers the long-term stability inherent in this type of thermometry, but it requires electronic circuitry to properly excite the resistance elements and electronic amplification of the PRT bridge output signal to produce a low impedance output signal. The robust structure of the thermal sensing surface restricts the response time of the instrument, and the response is recovered through electronic differentiation and feedback. The PRT design reflects state-of-the-art performance but at increased cost of manufacture.

The bismuth telluride thermopile design offers a high output coefficient, eliminating the need for electronic amplification, and also provides a low output impedance, making it suitable for driving long lines. Both the PRT and bismuth telluride designs require double-domed enclosures, which are the dominating manufacturing cost factors.

The bismuth antimonide design offers millisecond response time and does not employ expensive glass domes but rather an inexpensive diffusing foreoptic described by Harrison (1994). A shortcoming of the bismuth an-

Corresponding author address: David J. Beaubien, Yankee Environmental Systems, Inc., Airport Industrial Park, 101 Industrial Blvd., Turner Falls, MA 01376.
E-mail: djb@sunlight.yesinc.com

timonide thermal detector sensor is that it is highly temperature dependent and, as a result, the output coefficient is reduced by nearly two orders of magnitude by the required thermistor compensation circuitry. In addition, the output impedance of such a device is high compared to other thermopile types, suggesting that electronic amplification and impedance reduction should be employed with this instrument.

All of the thermal-converting types of pyranometers utilize common features: a black surface of uniform absorptivity to achieve the energy conversion and a controlled thermal structure. The incoming radiant energy flux is converted to a thermal flux in the black surface; the temperature of this surface rises until the heat flux leaving the surface is in equilibrium with the entering radiant flux. The temperature rise of the sensing surface above the temperature of the surrounding environment is then a measure of the heat flux and therefore is a measure of the incoming radiant energy. The heat rise in the sensing surface caused by the radiant energy flows to the surroundings by means of conduction through the solid supporting structure, by convection to the surrounding atmosphere, and by radiation to the surrounding structure. Hence, the temperature of the sensing surface depends on the surrounding environment as well as on the incoming radiation.

To render the solar irradiance measurement independent of the temperature of the environment, a temperature difference must be measured in such a manner that only the rise due to the incoming radiation is sensed. One approach is to utilize alternating black and white surfaces in an otherwise identical mechanical structure and then measure the temperature difference between these two surfaces. This has the advantage that the exposure of the surfaces to the environment can be made virtually identical such that changes in the ambient air temperature of the external environment have the same effect on both the sensing and reference surfaces. As a result, such an instrument can be made relatively free from the influence of external environmental transient temperature changes.

In instrument designs that utilize a single uniform (nonsegmented) black sensing surface to achieve axial symmetry and good cosine response characteristics, some aspect of the thermal symmetry of the sensing and reference surface is compromised. The temperature of the air directly above and in contact with the sensing surface is influenced by the temperature of the glass dome, which is in turn influenced by external ambient air temperature fluctuations. While the reference thermal structure is designed to see the same thermal influence, it is difficult to achieve the thermal symmetry that is achieved with the segmented black and white surfaces. As a result, two concentric hemispheres (the equivalent of a double-pane window) are generally utilized in black surface pyranometers to reduce the influence of external temperature transients. It is important to achieve axial uniformity in the design of the sensing surface because the reflection from the dome forms an optical caustic or cusp, which influences the measurement, and any nonuniformity in axial response is influenced by this area of increased radiation.

To summarize, both types of black surface pyranometers have advantages and drawbacks. Instruments using both black and white surfaces must contend with the uniformity and ultimate deterioration of the reflective and absorptive characteristics of both working surfaces. Black and white pyranometers suffer from asymmetric axial response unless adequate black and white segmentation is provided in the design of the surfaces. However, black and white pyranometers are less costly to manufacture because they can be built with a single optical glass protective dome since ambient air temperature changes as well as heating of the interior affect both surfaces in the same way. Single black surface pyranometers can be made free of axial errors but require two concentric optically ground domes: one to protect the instrument from the weather and a second to isolate the receiving surface from local heating. Since the optical domes are the most expensive components of the instrument, this increases the cost of this type of pyranometer.

Both types of pyranometers measure the temperature differentials using thermopiles (typically copper constantan), which are often quite fragile. Thermopiles produce an output of 5–15 μV W^{-1} m^2, with an output impedance of 1000 ohms or less. The output of a thermopile is nonlinear and is influenced by ambient air temperature changes. These influences are usually corrected by means of thermistor compensation circuitry. Such an instrument requires no power for its operation, which was an advantage during the era of mechanical recording galvanometers but is of less significance today due to the availability of AC line power, solar power, and rechargeable batteries at most data recording sites.

The WMO classifies pyranometers as ''high, good, and moderate quality'' instruments. ''High quality'' pyranometers, when individually characterized, are suitable for use as secondary standards; ''good quality'' pyranometers are acceptable for network applications; and ''moderate quality'' is acceptable for lower-cost applications. Specifications for the three classes of pyranometers can be found in WMO (1997).

The time response and ambient temperature compensation of most high quality thermopile pyranometers permit them to be classified as ''high quality'' and *when individually characterized*, are suitable for use as secondary standard instruments in accordance with the WMO criteria. The linear mechanical configuration of many thermopiles used in pyranometers results in azimuth and cosine (zenith) deviations from ideal behavior. Worst-case cosine errors greater than the $\pm$3% suggested for secondary standard pyranometers have been reported (Michalsky et al. 1995; Abhyankar et al. 1994). These specifications limit the performance of pyranometers but represent the current state of the art for this class of instrument.

The research reported in this paper has focused on examining new approaches to pyranometer design that offer reduced cosine and azimuthal errors, without compromising the time response, ambient temperature dependency, spectral characteristics, linearity, and long-term stability of the instrument. To achieve any improvement in the performance of an instrument, measurement methods and apparatus must first be defined, which will conclusively demonstrate that such improvements have, in fact, been made. Pyranometer designs invariably involve compromises on output level, speed of response, ambient temperature dependency, cosine (i.e., angular) and azimuthal responses, and cost to produce. It is most important that the cosine response be as close to ideal (Lambertian) as possible, and that azimuth errors be totally eliminated. Apparatus for conducting these tests is described in the appendix to this paper.

At the outset of this research a design philosophy was adopted to forego the need to be independent of electrical power in exchange for improved instrument performance since high quality solar irradiance measurements often require forced-air ventilation and instrument deicing. These requirements demand modest levels of electrical power on the order of 10–20 W. A second objective was to eliminate the fragile and azimuth-dependent nature of the radiation detector by replacing the thin blackened membrane typically used in a linear thermopile detector with a rugged, thermally conductive blackened metal disc to minimize thermal gradients and improve axial symmetry. A third objective was to reduce as much as possible long-term changes in the calibration coefficients of the instruments by employing a single, UV-stabilized black surface detector.

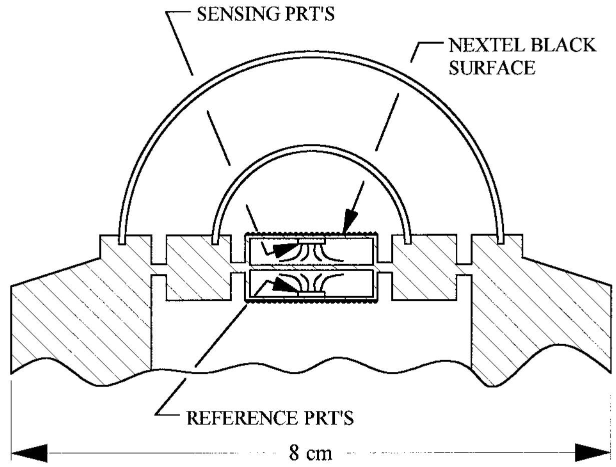

FIG. 1. Configuration of pyranometer using platinum resistance thermometers.

2. A pyranometer using platinum resistance thermometers

The first design uses platinum resistance temperature measuring sensors (PRTs) known to have excellent long-term stability. The mechanical cross section of this pyranometer is shown in Fig. 1. Two symmetrical vanadium steel alloy discs, each 24 mm in diameter and 0.008 mm thick, are electron beam welded to an Invar ring, which is thermally bonded to the body of the instrument. This symmetrical configuration is not new to pyranometer design (see Karoli et al. 1984) but is essential to ensure that all ambient temperature changes reach the sensing and reference thermometers at the same time and magnitude to produce a canceling effect on the bridge output.

Four thin-film PRTs are thermally bonded to the centers of the undersides of the discs: two on the top disc and two on the bottom reference disc. These are wired in a dynamic Wheatstone bridge configuration to produce the maximum output signal when a temperature difference exists between the two surfaces. In this configuration of the Wheatstone bridge, one thermometer from each leg of the bridge is mounted in the center of the top (sensing) surface, and the other in the opposing leg is mounted in the center of the bottom (reference) surface. The use of platinum resistance technology is not new to pyranometry; the original Callendar pyranometer (circa 1898) (Coulsen 1975) used an array of platinum wire grids in a black and reflective configuration to make a measurement of solar irradiance. An instrument of this type was deployed at the Botany School of the University of Cambridge, England, for more than 50 years and continued to offer a correlation coefficient of $r = 0.99$ with the British Meteorological Office pyranometer (Stanhill 1983). It is not known whether this stability is attributable to the use of platinum, but platinum resistance thermometers have evolved as the international standards for temperature measurements due to their inherent long-term stability.

Platinum resistance thermometers have a resistance-versus-temperature response that follows the Callendar–van Dusen equation and are essentially linear for limited temperature spans. The PRTs used in this instrument have a nominal resistance of 1000 ohms at 0°C and change their resistance approximately 3.95 ohms per degree Celsius. In order that the bridge have the same output coefficient for a given temperature rise at any ambient temperature, the PRTs must be excited by the same current at all temperatures since the net resistance of the bridge changes 3.95 ohms per degree Celsius as a function of ambient temperature. This requirement is met by exciting the bridge with a constant current source. Exciting the bridge with a constant current solves the problem of ambient temperature dependence, but small variations in the nominal resistance values as well as the resistance coefficients must be considered. For this reason, in order to minimize thermal tracking errors, the resistances of the four PRTs are matched to

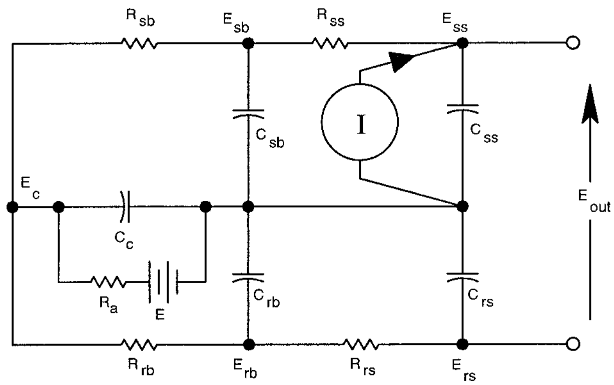

FIG. 2. Electrical analog of pyranometer detector.

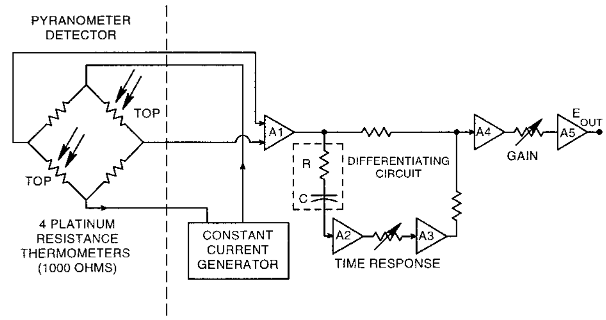

FIG. 3. Block diagram of platinum resistance thermometer-based pyranometer.

within 0.01°C at 0°C. Measurement of the bridge output over the range +50°C–−50°C under a constant level of radiation verified that the ambient temperature dependency of the bridge is less than 0.5% over that temperature range. No thermistor compensation circuitry is required.

The temperature of the center of the blackened metallic disc rises approximately 6°C when subjected (under two WG-295 glass domes) to 1250 W m^{-2}. The 24-mm disc intercepts approximately 565 mW of solar energy. The bridge is excited by a 1-mA dc constant current and has a net resistance of 1000 ohms at 0°C, and hence dissipates 1 mW total, or 0.5 mW, into the top surface, due to self-heating caused by the electrical excitation current. The bottom surface views the black walls of the instrument cavity. The temperature rise caused by this self-heating is the same on both sides of the structure and is less than 0.1 of 1% of the solar heating and therefore has minimal effect on the measurement.

a. The electrical analog of the PRT-based pyranometer

An electrical analog of the detector head is presented in Fig. 2.

The pyranometer was designed to have a symmetrical thermal balance and can be viewed electrically as a balanced bridge circuit. It is balanced with respect to the ambient temperature, but the incident radiation is not canceled from the output. Construction consists of two identical thermal sensing structures: a top sensor that is exposed to the solar radiant energy and a second reference sensor that is shielded from the sun. The designated components and nodes in the analog are as follows:

- I incoming solar radiation
- E ambient temperature
- R_a coupling from the ambient temperature to the instrument case
- C_c thermal capacity of the instrument case
- E_c temperature of the instrument case (in the steady state this is equal to the ambient temperature)
- R_{sb} thermal resistance from the case to the base structure
- E_{sb} temperature of the reference structure
- C_{sb} thermal mass of the reference structure
- R_{ss} thermal resistance from the base of the sensor to the sensing surface
- E_{ss} temperature of the active sensing surface
- C_{ss} thermal mass of the active sensing surface
- E_{out} output signal equal to the temperature of the active sensing surface minus the reference

The structure of the reference surface is identical to the active sensing structure so that the values of thermal resistance and thermal capacity are the same in both. The components for the reference side of the bridge are labeled in like fashion to those of the sensing side except the first subscript is "*r*" for reference instead of "*s*" for sensor.

When component values on both sides of the circuit are identical, there is zero output for both the steady state as well as for transient changes in the ambient temperature. Hence, only radiant incoming energy represented by the current source results in an output signal.

b. Block diagram of PRT-based pyranometer

A simplified block diagram for the platinum-based instrument is shown in Fig. 3. The radiation detecting circuitry is shown to the left of the dotted line and consists of the four matched 1000-ohm PRTs. The bridge output for a 1250 W m^{-2} excitation is approximately 24 mV dc. The substantial output signal generated by the bridge combined with the symmetrical (identical) bridge component fabrication results in negligible thermocouple voltages (copper/platinum, in this case).

The robust structure, introduced to offer fewer thermal gradients, yielded a relatively slow time response, which was compensated for electronically following Brinkworth et al. (1976). A chopper-stabilized amplifier provides a gain of 100, resulting in 2.40 V dc at the output of the first stage. A portion of this signal is differentiated by the series resistance–capacitance network shown in the dotted box in Fig. 3, then further amplified and added back to the original signal at the input to the buffer amplifier. The radiation receiving surface has a natural thermal time constant of 10 s. The amplifier utilizes a pole-canceling compensator that results in an output with a 1-s single-pole response. This enhances the time response of the instrument by a factor of 10, thereby eliminating the need for a fast responding and hence delicate thermal sensing surface.

The solar output coefficient of the pyranometer is 2.00 mV W^{-1} m^2, providing a 2.50-V dc, low-impedance output signal for an irradiance of 1250 W m^{-2}. The electronic circuitry exhibits less than a 0.1% change in gain over an ambient temperature span of -50°C to $+50$°C. Not shown in the block diagram are ''housekeeping'' components for power conditioning, input power surge protection, and output short circuit protection.

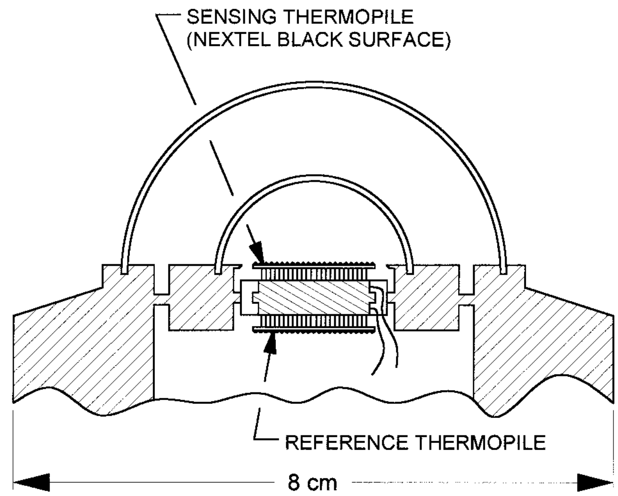

FIG. 4. Cross section of bismuth telluride black surface pyranometer.

3. A pyranometer using a 76-element bismuth telluride thermopile

A second approach to improving pyranometer performance involved the use of a multijunction bismuth telluride thermopile. Bismuth telluride is a semiconductor material used for thermoelectric heat pumping applications. It has a Seebeck coefficient of approximately 200 μV dc °C^{-1} and has a highly linear output characteristic within the thermal regime of $+50$°C to -50°C. A circular (rather than lineal) array of such thermopiles can produce a substantial output voltage at a very low impedance making it ideally suited to the pyranometer application. A similar design employing a single bismuth telluride thermocouple element in a black and white pyranometer has been previously described by Proctor et al. (1982). Improvements in thermoelectric module technology offer higher output coefficient and better axial response in the design described.

A mechanical cross section of such a pyranometer is shown in Fig. 4. As in the platinum resistance thermometer design described previously, a symmetrical thermal design is used to ensure that ambient temperature-induced gradients affect both detectors at the same instant and at the same magnitude. The thermal symmetry was tested by subjecting the pyranometer to a step change in temperature and monitoring its output for changes. The temperature response to a 20°C step change is less than 1% of full-scale output.

Two concentric WG-295 glass domes are utilized. Two matched 76-element bismuth telluride thermopiles are connected in electrical opposition such that any thermal changes introduced by changes in ambient temperature are canceled out. One surface is exposed to solar radiation, while the other remains unexposed, viewing the black walls of the pyranometer housing. The resulting configuration produces an output as a function of the radiative heating of the top surface only and requires no compensation schemes for changes in ambient temperature. The surfaces consist of two discs of 2-cm-diameter, 0.8-mm-thick sterling silver. These discs are bonded to the thermopiles with high conductivity silver-filled epoxy. The radiation surfaces are coated with Nextel black suede applied with an artist's airbrush. The configuration shown has a 1/*e* time constant of 12 s. The electrical analog of this instrument is not significantly different from that of the PRT model described previously.

The bismuth telluride pyranometer produces an output of approximately 80 mV when exposed to 1250 W m^{-2}, at an output impedance of less than 2 ohms. It is well suited to driving long signal lines without further amplification.

Due to the thermal uniformity of the radiation detecting surfaces, the instrument has axial errors of less than 0.1%, which was the limit of resolution of the axial test apparatus.

4. A pyranometer using a diffusing foreoptic with a bismuth antimony thermopile

Field experience (Harrison 1994) with a diffusing foreoptic offering good Lambertian characteristics prompted the investigation of its use in a third pyranometer design. This instrument uses a fast response thin-film bismuth antimony thermopile with a black receiving surface. Such a configuration is shown in Fig. 5.

The thin-film thermopile used in this instrument is optically black coated and spectrally flat from 300 to 3000 nm. It has a 1/*e* response of 40 ms, which differentiates it from all other black surface pyranometers. Most photodiode pyranometers offer fast response but are not WMO-classified for meteorological use because they do not exhibit a flat spectral response over the solar spectrum. Whether the fast response offered by this design is beneficial depends on the application of the pyr-

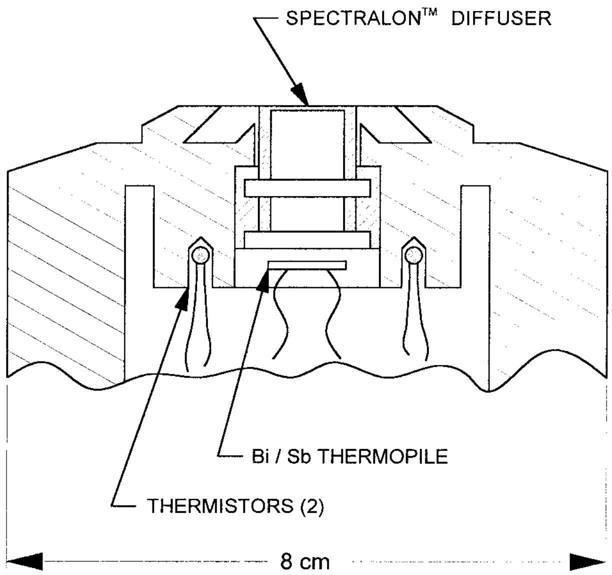

FIG. 5. Cross section of a diffusing foreoptic thin-film bismuth antimonide pyranometer.

anometer. The diffuser is fabricated from Spectralon™, a material having uniform optical transmission properties from the UV well into the near IR (Labsphere 1990). The diffuser allows an angular response to nearly $\pm 85°$ to be obtained with a thermopile without a covering dome having a much poorer angular response, typically $\pm 50°$. The use of the diffuser eliminates the need for more costly optically ground protective glass domes. The diffuser scatters all incoming radiation in its cavity tending to produce a uniform axial response from the instrument. Axial errors on this configuration were below the 0.1% limit of resolution of our axial test facility.

The bismuth antimony thermopile exhibits a 4% per degree Celsius negative temperature dependence that is compensated for by a thermistor network that comprises two thermistors thermally bonded to the thermally conductive block that houses the thermopile. This network reduces all ambient temperature-induced errors to less than $\pm 0.1\%$ between $+50°$ and $-50°C$. The compensation network also acts as a divider on the thermopile output signal; the output signal for 1250 W m^{-2} exposure is approximately 2 mV dc, resulting in a coefficient of 1.6 μV W^{-1} m^2.

5. Characterizations of the three pyranometers

Tests designed to characterize the performance of pyranometers have been developed (Zerlaut 1989; Harrison 1994) but require specialized facilities and are tedious. The resolution we obtained with our facilities in typical characterization tests was seldom better than 1%. In the characterization tests for the three new pyranometers, we have presented the results graphically for measurements that exceed the 1% level; for results below 1%, we present them as simply "below 1%."

a. Time response of the pyranometers

The time response ($1/e$) of the basic thermal detection scheme for the PRT-based pyranometer without electronic enhancement is approximately 10 s, and electronic compensation is used to enhance the time response to approximately 1 s. The time response of the bismuth telluride thermopile pyranometer is approximately 12 s and the time response of the thin film bismuth antimony pyranometer is approximately 40 ms.

b. Ambient temperature responses of the pyranometers

A fundamental requirement of any pyranometer is that its response be a function of the prevailing solar irradiance and not to changes in ambient air temperature. In the PRT and bismuth telluride pyranometers, this is accomplished by the symmetrical arrangement of the detectors. The three pyranometer designs were subjected to upward and downward 20°C step changes in ambient air temperature, typically from 20° to 40°C and 20° to 0°C, while in a darkened environmental chamber with their outputs monitored. Change in output for a 20°C step change was approximately 1% of the full-scale output (i.e., 12.5 W m^{-2}) of the instrument, returning to less than 0.1% of the initial dark output value in approximately 15 min.

The response to 20°C step changes of the thin-film bismuth antimony pyranometer was less than 1% of the full-scale (one sun) output for the pyranometer, verifying the effectiveness of the compensation network.

c. Azimuth response tests on pyranometers

A pyranometer's response should not change with azimuth—introducing so-called axial or azimuthal errors. This type of error is well documented for several widely used pyranometers and can run as high as 5% at 15° solar altitude (Zerlaut 1989).

To test for uniform azimuth response, the pyranometer is mounted on a rotary table and illuminated by means of a high intensity lamp at a low solar elevation angle. The azimuth errors of the platinum resistance unit and the bismuth telluride unit are less than 1% at 30° solar elevation angles and appear to be random, resulting from the sum of dome misalignment and mechanical leveling errors. The axial error for the diffuser type is less than 0.1% and is below the limit of resolution of the azimuth test apparatus employed and shown in the appendix.

d. Cosine (angular) response tests

The cosine (or Lambertian) response is one of the most significant specifications for any instrument pur-

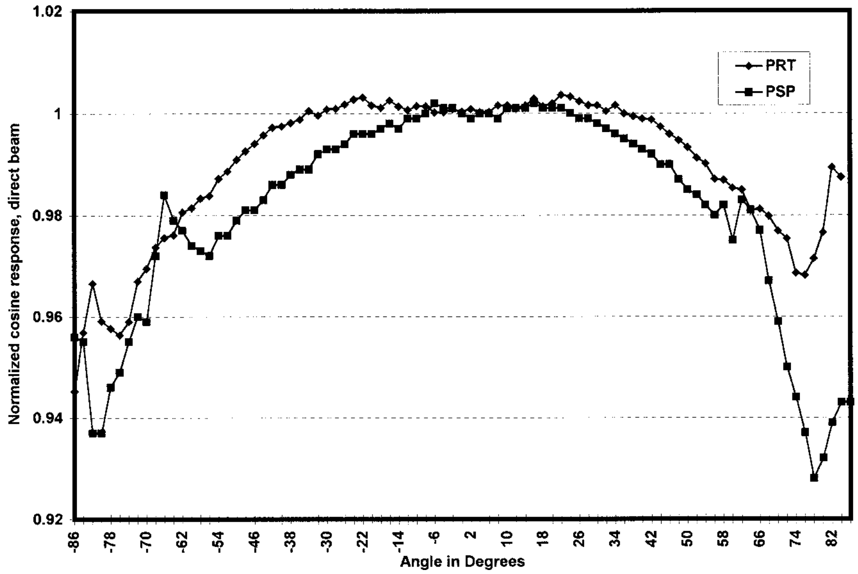

FIG. 6. Deviation from direct beam cosine responses for PRT-based and bismuth telluride pyranometers.

porting to measure global solar irradiance. The cosine response of the pyranometer defines the degree of precision to which the instrument can properly resolve the incoming radiation into its normal component.

Cosine response tests are best made using the sun as the source but require extended clear sun periods that can be difficult to obtain in a timely manner. For the expediency required in testing quantities of instruments, a laboratory procedure for determining cosine response has evolved employing a direct beam apparatus patterned after a design reported by Harrison (1994). Our version of the apparatus uses a 500-W xenon–mercury arc lamp as source with the addition of feedback stabilization for the source. The cosine test facility is cross checked several times a year (using production radiometers) with the facility at the University at Albany, State University of New York to ensure good correlation in the methodology. Whether the response of a pyranometer determined by direct beam only is representative of the behavior of the instrument in the field is moot, but it at least allows the cosine response of different types of pyranometers to be compared. A brief description of the apparatus is given in the appendix.

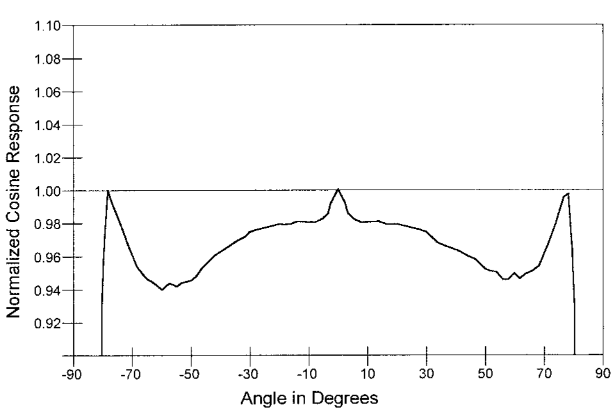

FIG. 7. Deviation from a true cosine response for the diffusing fore-optic bismuth antimonide pyranometer.

Twenty-five of the PRT and bismuth telluride pyranometers were tested for direct beam cosine response; Fig. 6 shows data for a typical PRT unit, together with the direct beam response of a PSP (S/N 27965F3). All PRT units tested exhibited deviations from a true Lambertian response of less than $\pm 2\%$ between zenith angles of $\pm 75°$ and less than $\pm 3\%$ between $\pm 80°$. Responses on Eppley PSPs and three Kipp and Zonen CM21s as reported by Michalsky et al. (1995) exhibited deviations from ideal direct beam cosine behavior as much as -10% between zenith angles of $\pm 75°$. The deviation from a true Lambertian response for the bismuth telluride instrument is essentially identical to that of the PRT pyranometers due to the similarity of construction.

The deviation from a true cosine response for the thin-film bismuth antimony pyranometer as measured on our apparatus is shown in Fig. 7 and is defined primarily by the cosine response characteristic of the diffuser, which has been well documented by Harrison et al. (1994).

e. Linearity tests

Linearity tests on the pyranometer designs consisted of illuminating the instruments with a standard FEL quartz lamp at distances of 25, 50, and 100 cm, and then checking adherence to square law behavior. Although linearity testing by this method was not extensive, results indicated that the instruments deviated less than 1% from a linear response, which was the limit of resolution of our apparatus. These results are consistent with those found for other black surface pyranometers (Zerlaut 1989).

f. Calibration issues

The absolute calibration coefficients for pyranometers in units of microvolts per watt meters squared should be traceable to an internationally accepted reference, such as that maintained at the World Radiation Center (WRC) in Davos, Switzerland, or one of the regional laboratories that maintains traceability to the WRC reference. Several calibration methods are presented in WMO-8, all of which involve exposure to the sun under a variety of sky conditions. The calibration coefficients presented for the three pyranometers were obtained by using a WRC-traceable pyranometer and also by using a normal incidence pyrheliometer for the direct component and a shaded pyranometer for the diffuse component. The calibrations were run over a period of several days using a 16-bit multichannel data acquisition facility. No significant advantage was apparent in using the more tedious normal incidence pyrheliometer/shaded pyranometer method over the direct comparison method as long as the calibrations were conducted at solar elevation angles of 45° or greater.

Attempts to obtain calibration coefficients during the winter months at our higher latitude with attendant small solar elevation angles are difficult. Calibrations using standard lamps and integrating spheres did not produce consistent results, once again supporting the observation that *there is no substitute for using the sun as the source for absolute calibration of pyranometers.*

g. Fabrication methodology

Considerable attention must be paid to certain aspects of the pyranometer fabrication.

1) Alignment of the plane of the sensing surfaces to the plane of the instrument level. This is accomplished before the receiving surface is coated with black paint. The pyranometer is mounted and carefully leveled on a rotating table of the type used for axial error tests. The rotating table level and instrument level should be checked for a constant reading while the table is rotated throughout 360°. A laser pointer is then reflected off the edge of the unpainted surface at an elevation angle of about 60°, and the resulting reflected spot on the ceiling monitored as the instrument is rotated. The amount of mechanical misalignment of the detecting surface can then be determined from the geometry of the setup and eliminated by appropriate adjustments to the detecting surface. Failure to maintain perfect leveling results in axial errors and an asymmetric directional response.
2) Coating the metallic detection surfaces. This is best done after the level check. The radiation absorbing surfaces used in the instruments must be properly prepared before coating with the Nextel black paint system. The vanadium alloy used in the PRT instrument is particularly difficult to bond, and the silver disc used in the bismuth telluride pyranometer must first be roughened and gold flashed to ensure good bonding and elimination of the tarnish problems associated with silver. The surfaces must be thoroughly free of oils and particles before a very thin layer of Nextel primer is applied by airbrush. A slowly rotating work table facilitates this operation. The final black coating is then applied, again by airbrush, striving to obtain a uniform thickness but rough surface, by spraying from a distance so as to encourage partial drying of the particles before final arrival on the surface. The entire surface is then baked out at 100°C for 24 h. Finally, the entire surface is mounted under a UV lamp for 1 week to preage the surface against UV solarization. This procedure results in very consistent long-term stability of the surface.
3) Installation, alignment, and mechanical concentricity of the double domes. One of the phenomena encountered with instruments employing domes is the development of an optical cusp or caustic as the sun angle decreases. This cusp is visible at the lower solar altitude angles on most pyranometers and causes an area of increased heating on the black receiving surface. The effect of this cusp is to offset the loss of pyranometer output at low sun angles due to the reflections from the black surface. It is important that the effect of the cusp be the same at all azimuth angles. To ensure that this is the case, the domes must be of uniform wall thickness and be located concentric with one another. Domes with as little as 0.1-mm asymmetry of mounting can exhibit axial errors as large as 3%. Proper mechanical alignment and fixturing of the domes must be employed to minimize this source of error.
4) Reflection/refraction of light within the dome system. The interface of the ground edge of the optical dome with its mounting ring can be a source of error if the adhesive system is not designed to minimize reflection of scattered light within the dome glass. This is especially important to minimize cosine enhancement at low sun angles. The outer dome adhesive system must also be capable of withstanding the rigors of the environment. Multiple component adhesive systems are used to minimize this problem.
5) Treatment and field maintenance issues for instruments using Spectralon™ diffusers. Although instruments using Spectralon™ diffusers are less costly to manufacture and exhibit good cosine responses, it must be remembered that the diffuser surface is quite fragile and care must be exercised to preserve the mechanical and surface integrity of the device. In the field, periodic cleansing with mild detergent and water is mandatory to minimize errors.

TABLE 1. Comparison of three pyranometers.

Characteristic	Platinum resistance	Bismuth telluride	Bismuth antimonide
Resolution (smallest detectable change in W m^{-2})	± 1	± 1	± 10
Stability (percentage of full scale, change/year)	$< \pm 1$	Undetermined	Undetermined
Cosine response (percentage deviation from ideal at 10° solar elevation on a clear day)	$< \pm 3$	$< \pm 3$	$+0, -6$
Azimuth response (percentage deviation from the mean at 10° solar elevation on a clear day)	$< \pm 1$	$< \pm 1$	$< \pm 1$
Temperature response (percentage maximum error due to change of ambient temperature within the operating range)	± 1	± 1	± 1
Nonlinearity (percentage of full scale)	± 0.5	± 1	Not measured
Spectral sensitivity (percentage deviation from mean absorpance 0.3–3 μm)	± 2	± 2	Not measured
Response time (1/*e* response)	1 s	12 s	40 ms

6. Conclusions

The performance specifications for the three pyranometers are compared in Table 1.

The three pyranometers are similar in performance in that they all offer very low azimuth errors, are generally insensitive to changes in ambient temperature, and offer the spectrally uniform 300–3000-nm response of the black surfaces. The PRT instrument meets or exceeds the WMO specifications for a ''high quality'' pyranometer, and the bismuth telluride and bismuth antimony thermopile units meet the WMO requirements for use in networks.

The introduction of thin-film platinum resistance thermometry to the design of a thermally balanced pyranometer allows the use of a robust detection surface, resulting in improved thermal, azimuthal, and cosine response characteristics. The increased time response caused by the increased mass of the surface is offset by the use of electronic compensation, and the use of electronic gain results in high-level, low-impedance output signal. Platinum resistance thermometry is known to have excellent long-term stability and serves as the international standard for thermometry; however, whether the use of the PRT will result in longer periods between calibrations will be known only after a statistically significant quantity of instruments are operated in the field for extended periods. Ten instruments of this type have been operated on an outdoor test stand for a period of 1 year without any discernible shift in calibration coefficients when compared to an Eppley PSP as a reference. The PSP was stored indoors when not in use as a reference. The coefficient for the PSP reference changed from 8.92 to 8.87 μV W^{-1} m^{-2} (0.56%) over the 2-yr period between its WRC-traceable recalibrations. The compromise in a design of the PRT type is that 1) power is required to operate the bridge circuit and attendant electronics and 2) the cost of these components is reflected in the instrument.

The bismuth telluride thermopile pyranometer offers excellent cosine response, a very low output impedance, and output coefficients an order of magnitude higher than those obtained from other thermopile instruments. Its 1/*e* response of 12 s is adequate for most climatological and meteorological applications.

The bismuth antimony thin-film thermopile with Spectralon™ diffuser may be useful in evaluating photovoltaic panels and other applications in which a fast response is important. This design is compromised by the instrument's lower output coefficient and has somewhat higher output impedance than conventional pyranometers.

Acknowledgments. This work was supported in part by a Small Business Innovation Research Grant from the U.S. Department of Energy.

APPENDIX

Test Apparatus

The apparatus used for conducting the azimuth tests is shown in Fig. A1. A rotary table equipped with lev-

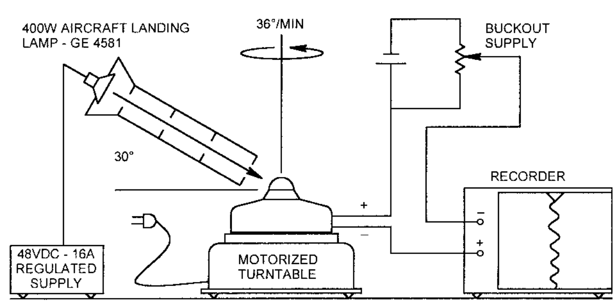

FIG. A1. Apparatus for pyranometers azimuth error tests.

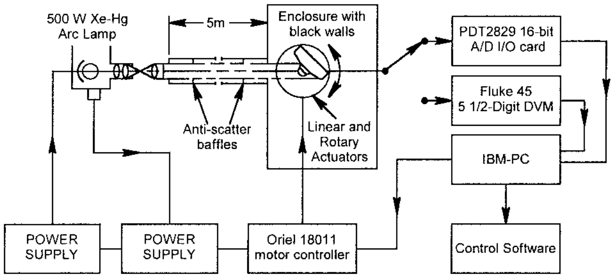

FIG. A2. Apparatus for determining direct beam cosine response of pyranometers.

eling screws and a precision bubble level serves as the platform for the instrument under test. The illumination is provided at an angle of 15° by means of a 400-W aircraft landing lamp located approximately 2 m distant. This lamp requires 28 V dc and 16 A, which is furnished by a regulated supply to eliminate influences from changes in power line voltages. This light source need not be uniform, but its output must be stable for the duration of the test. The output of the instrument under test is connected differentially with a reference voltage, and the deviations from zero output are recorded as the instrument is rotated at a low speed, typically 36° $\min^{-1}$, requiring 10 min for a full test.

The apparatus used to obtain cosine responses is patterned after a system described by Harrison et al. (1994) and is shown in Fig. A2. A 500-W halogen-free xenon arc lamp is used as the source. A photofeedback control system on the lamp (not shown) helps ensure stability over the period of the test. A 5-m-long collimator provided with 5-cm-diameter stops produces a beam with less than 1° of beamspread and provides a flux of approximately 125 W m^{-2} at the working plane. The variation across the beam is less than 0.1 of 1%, as measured with a silicon diode furnished with a 0.1-mm-diameter pinhole, scanning the beam orthogonally.

The instrument to be tested is mounted on a computer-driven rotary table programmed to turn in 1° steps from −90° to +90°. The amount of time spent at each step can be programmed and is typically 2 min to permit all gradients and responses to settle out. At each step, 100 measurements are acquired, averaged, and stored by the data collection system. A typical cosine test requires approximately 6 h to complete.

REFERENCES

Abhyankar, V. V., V. V. Kanade, and S. V. Prabhu, 1994: Maintenance of radiation standards in India. Instruments and Observing Methods Rep. 57, WMO/TD-No. 588, 328 pp. [Available from World Meteorological Organization, Case Postale 2300, CH-1211 Geneva 2, Switzerland.]

Brinkworth, B. J., and T. D. R. Hughes, 1976: Accelerated response of thermopile pyranometers. *Sol. Energy,* **18,** 404–407.

Coulsen, K. L., 1975: *Solar and Terrestrial Radiation.* Academic Press, 322 pp.

Frohlich, C., and J. London, 1986: Revised instruction manual on radiation instruments and measurements. World Climate Research Program, Publication Series No. 7, WMO/TD-149, 156 pp. [Available from World Meteorological Organization, Case Postale 2300, CH-1211 Geneva 2, Switzerland.]

Harrison, L. C., J. J. Michalsky, and J. Berndt, 1994: Automated multifilter rotating shadow-band radiometer: An instrument for optical depth and radiation measurements. *Appl. Opt.,* **33,** 5118–5125.

Karoli, A. R., J. R. Hickey, and R. G. Frieden, 1984: Self-calibrating cavity radiometers at the eppley laboratory: Capabilities and applications. *Proc. Recent Advances in Pyranometry,* Downsview, ON, Canada, International Energy Agency IEA Task IX Solar Radiation and Pyranometer Studies, 78–92.

Labsphere Spectralon,™ 1990: Tech. Bull., 4 pp. [Available from Labsphere, Sutton, NH 03260.]

Michalsky, J. J., L. C. Harrison, and W. E. Berkheiser III, 1995: Cosine response characteristics of some radiometric and photometric sensors. *Sol. Energy,* **54,** 397–402.

Proctor, D., and E. S. Trickett, 1982: An improved pyranometer. *Sol. Energy,* **29,** 189–194.

Stanhill, G., 1983: The distribution of global solar radiation over the land surfaces of the earth. *Sol. Energy,* **31,** 95–104.

WMO, 1997: WMO-8 Guide to Meteorological Instruments and Methods of Observation. Secretariat of the World Meteor. Org. [Available from World Meteorological Organization, Case Postale 2300, CH-1211 Geneva 2, Switzerland.]

Zerlaut, G. 1989: Solar radiation instrumentation. *Solar Resources,* R. L. Hulstrom, Ed., The MIT Press, 173–308.