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FINAL REPORT

The Calibration of Solar Radiation Measuring Instruments

by

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Foreword

This project was taken on with an almost blissfull ignorance of effort required. This was intended to be a project to collect information on the procedures for calibrating solar radiation measuring instruments. We expected all those procedures to be out there somewhere. All we had expected to do was to go and get them, to combine them into a report, weeding out the duplications and the unnecessary or useless ones. The situation we encountered was quite different.

The procedures were seldom documented precisely for a variety of reasons. Manufacturers producing hundreds of instruments per year had embodied the necessary procedures into the training of their personnel. Personnel turnover was very low. Laboratories performing many calibrations tended to vary their procedure depending on their immediate needs and upon the history of instruments being calibrated. In general those persons performing a large number of calibrations knew well what they were doing and understood their instruments thoroughly. Those performing only a few calibrations were prone to errors, primarily due to a lack of understanding of the instruments themselves and how they performed.

We had originally expected to be able to prepare a standardized set of procedures to be applied to all or most instruments, which could then be adopted by all as standard procedures. We learned that this is not possible and in fact not even appropriate at this point. Before describing procedures for calibration one must impart a thorough knowledge of the principles behind the measurements which are to be made; then an understanding of the instruments themselves and their performance. Only then do the procedures become meaningful. Once this knowledge is imparted a careful experimenter can develop his own procedure to suit his own situation best. For these reasons this report focuses on summarizing that knowledge as much as on procedures.

Recent developments in the field of solar radiation measurement have created a situation where the instrument calibrations themselves are the limiting factor in our ability to measure solar radiation with precision, (calibration here refers to our knowledge of the instruments' performance). There is definitely a need for more work in the area of instrument calibration.

This project should be followed up by a program to carefully evaluate the instrument characteristics described in Part II of this report, to establish which are characteristic model traits and which are variable, and the amount of variation expected. The results should be published in the open literature, not in organization internal reports.

Part I. Solar Radiation Measurement-Instruments and Some Types of Errors

INTRODUCTION

A user who is serious about making measurements of solar radiation must have a reasonably complete knowledge of the optical and physical character of the instruments used, and of the character of solar radiation itself. He must also understand the need for calibration and the limitations of various calibration methods.

One who calibrates solar radiation instruments must have a detailed knowledge of the optical and physical character of the instruments, and of the character of solar radiation. The processes involved in calibration need not be complex provided a thorough understanding of these characteristics is applied.

Part I of this report is a condensation of information gathered from many documents and people working in the field. It is an attempt to impart the necessary knowledge to prospective users or calibrators of solar instrumentation.

Part II of this report contains a definition of calibration in the context used in this report, and procedures for calibrating solar radiation measuring instruments.

An appendix to this report contains a description of various agencies who perform calibration of solar instruments and a description of the methods they used at the time this report was prepared.

SOLAR RADIATION MEASUREMENT

The Nature of Solar Radiation

There are three factors of primary importance in the measurement of solar radiation. These are 1) the wavelength of the radiation, 2) the intensity of the radiation at each wavelength, and 3) the direction from which the radiation comes. The different intensities of the radiation at different wavelengths give the radiation its spectral characteristics or color. Radiation from different directions often have different colors and different intensities. For example, the clear sky is blue, the sun is orange; clouds are white, and reflected solar radiation from the ground or other objects will have a variety of colors. Radiation coming directly from the solar disc (direct beam radiation) is many times greater in intensity than the radiation coming from clouds or from the clear blue sky (diffuse radiation).

This report is concerned with the measurement of the solar spectrum as a whole from about 0.3 to about 3.0 micrometers in wavelength, and not with the measurement of the spectral nature of that spectrum or the amount of energy at each wavelength. However, it is important to understand the spectral nature of solar radiation because different detectors have different responses as a function of wavelength and thus can give different results. This report is not concerned with solar radiation in the form of particles, x-rays, gamma rays or the "solar wind".

The solar spectrum outside the earth's atmosphere is illustrated in Figure 1. The spectral character of that extraterrestrial radiation (ETR) and its intensity is essentially constant. As that radiation passes through the atmosphere, it is absorbed, scattered and reflected causing changes in the spectral character of that radiation. The intensity at some wavelengths is reduced more than at others. This is also illustrated in Figure 1. An excellent description of this process has been prepared by D. Watt.*

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*D. Watt. On The Nature and Distribution of Solar Radiation, pub. March, 1978 by U. S. Govt. printing office #016-000-00044-5.

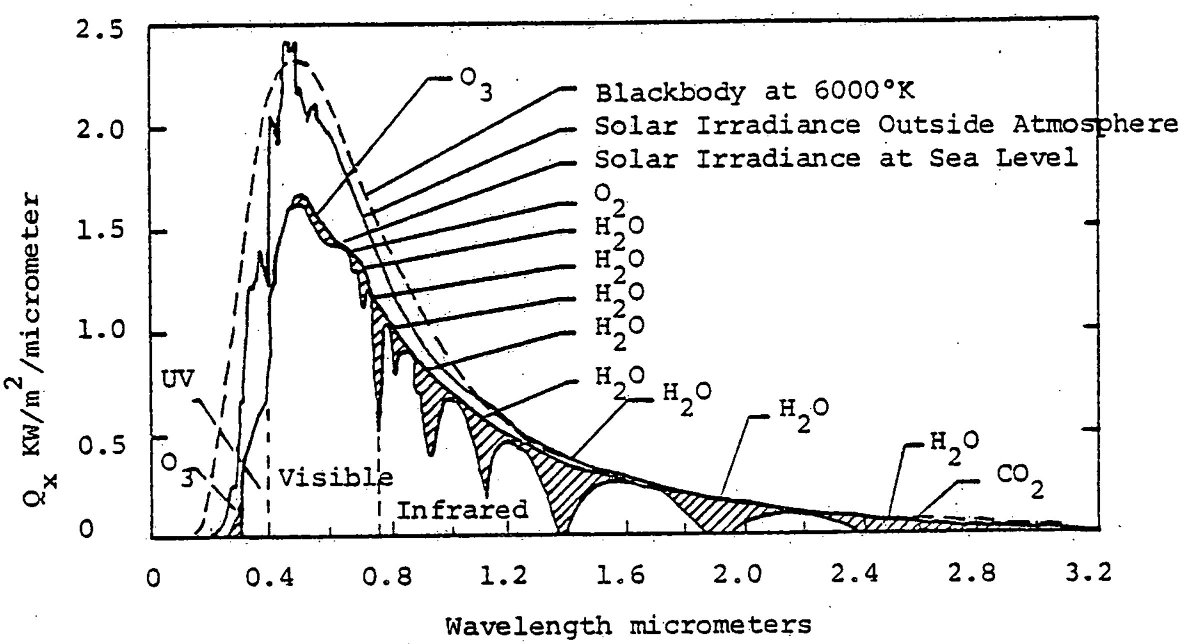

Figure 1. Solar Spectral Irradiance for Clear Sky*

The amount of this reduction is a function of the molecular content of the atmosphere, as well as the path length of the radiation through the atmosphere. Thus the direct beam at noon will have a different spectral content from that near sunrise or sunset because the path length through the atmosphere is longer in the latter cases. This path length also varies as a function of elevation of the observer and time of year. Smog, dust, haze and many other atmospheric effects also change the spectral content of solar radiation. All of these tend to reduce the blue end of the distribution near 0.4 µm more than the infrared at 0.8 to 3.0 µm because the shorter wavelengths are scattered more.

*Adapted from Figure 9.1, A. K. Ångström, "On determinations of the atmospheric turbidity and their relation to pyrheliometric measurements," Chapter 9 of Advances in Geophysics, V 14, Academic Press, 1970.

It is worth noting in Figure 1 that water vapor is the most sig-nigicant factor in reducing the solar spectral content, and that these bands are in the infrared portion of the spectrum and hence are in-visible to the human eye. The effects of clouds are not illustrated in Figure 1. It is also worth noting that roughly 7% of the solar energy reaching the earth's surface is in the ultraviolet, and that the remainder is roughly half visible and half infrared.

Blackbody Radiation

Figure 2 illustrates the blackbody radiation curves for a source like the sun and one at the average temperature of the earth. As the temperature of an object increases, the curve retains the same shape, but moves to the left along the horizontal axis in Figure 2. Note that while there is little overlap in the two curves shown at the top of Figure 2, that as an object is heated more and more, there is greater overlap under the curves. Blackbody radiation is an impor-tant element in the operation of some types of solar sensors.

Tungsten lamps (which are sometimes used as calibration sources) radiate as blackbodies and their spectral character is a strong func-tion of their temperature.

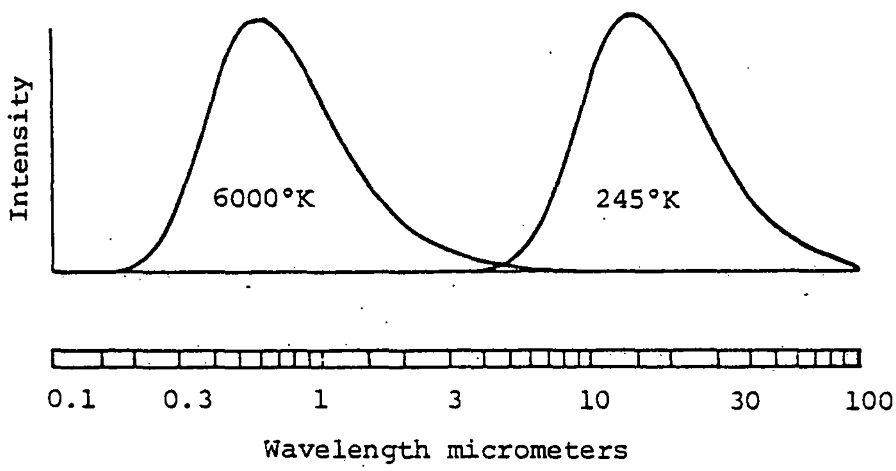

Figure 2. Blackbody emission curves for 6000°K and 245°K. The approximate emission spectra for the sun and earth re-spectively.*

*Adapted from Figure 10.3, G. D. Robinson, "Some meterological aspects of radiation and radiation measurement," Chapter 10 of Advances in Geophysics, V 14, Academic Press, 1970.

The Spectral Response of Solar Radiation Detectors

The ideal solar radiation detector will have a "flat" response from 0.3 to 3.0 microns and zero everywhere else. This is illustrated in Figure 3. Many detectors come fairly close to this ideal response, but none are precisely as shown in Figure 3. This deviation from the ideal causes considerable confusion and error in the calibration of solar instruments.

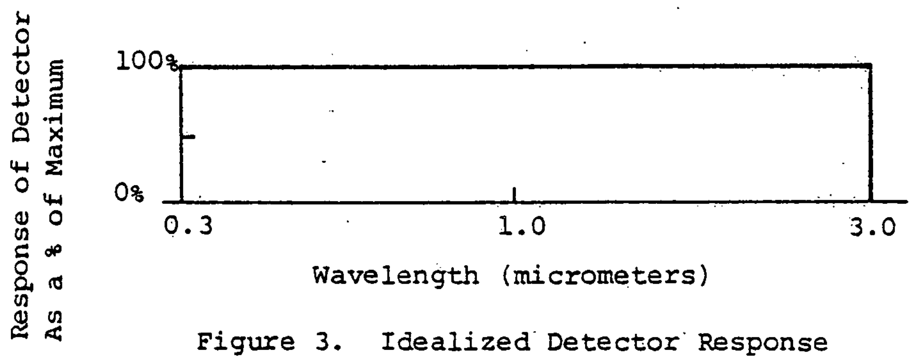

Figure 3. Idealized Detector Response

This variation among detectors is caused by many factors including:

1. Transmission of cover glass windows or instrument coatings.
2. Variations in the spectral character of the paint or absorbing surfaces, or reflecting surfaces.
3. Variations in the electrical nature of the detector mechanism (particularly in photovoltaic detectors).
4. Variations in the methods of heat removal or cooling of the instruments, or operating temperatures of the instruments (particularly in thermal detectors).

Photovoltaic detectors have a spectral response characteristic which is definitely not flat. A typical response curve is shown in Figure 4.

A number of conclusions are worth drawing at this point:

If a solar radiation detector does not have the desired flat spectral response from 0.3 to 3.0 µm, its calibration, as compared to one that does, will vary with atmospheric conditions.

Two solar radiation detectors with the same spectral response would agree even if their response was not flat, but would not agree with a unit that did have a flat response or a different spectral response, under changing atmospheric conditions.

Two different models of radiation detectors that may agree in sunlight may differ by several percent in artificial light, which has a spectrum different from sunlight.

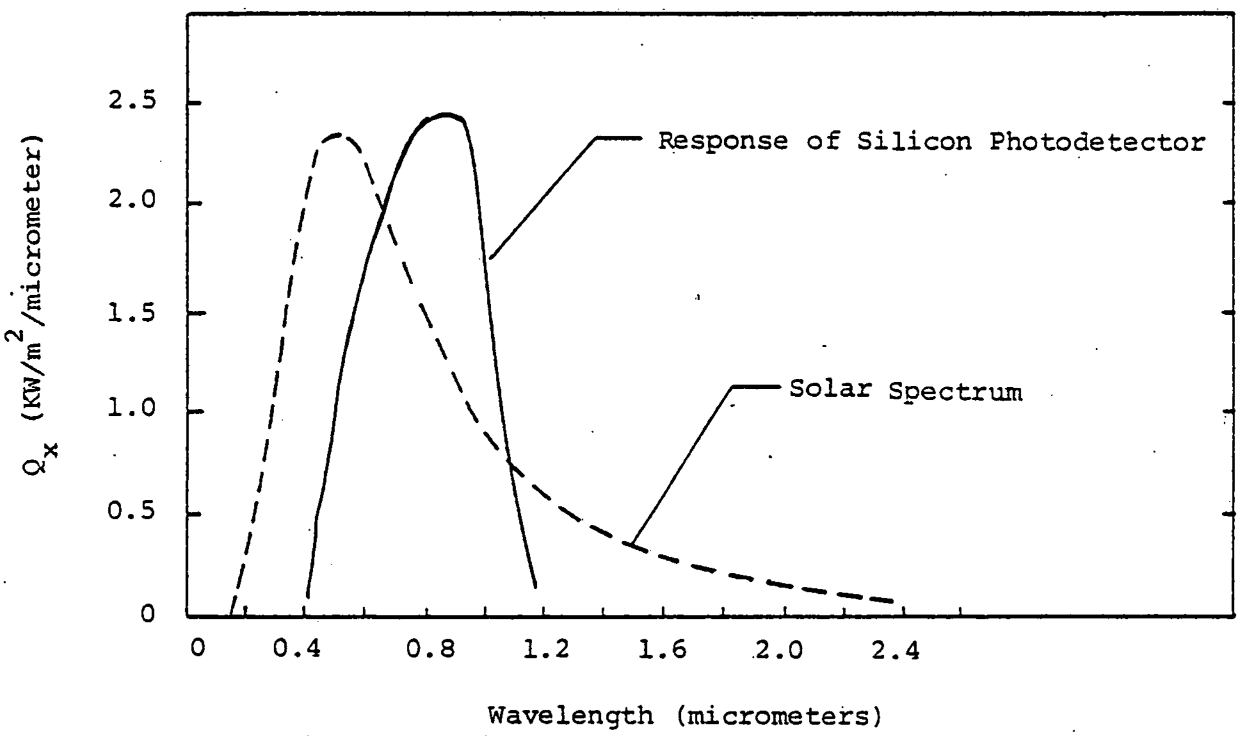

Figure 4. Spectral Response of Silicon Photodetector

Directional Characteristics of Solar Radiation

Most of the energy received by a solar radiation sensor on a clear day comes directly from the solar disc, this is called direct beam energy. As the sun moves across the sky dome throughout the day, the direction from which that energy comes changes. Any changes in directional sensitivity of the solar radiation measuring instrument are reflected as changes in the output or apparent changes in the amount of solar energy available. Annual variations in the solar declination have an additional effect. Figure 5 illustrates the path of the sun across the sky dome for one latitude.

Energy coming from the remainder of the sky dome, not directly from the solar disc, is called diffuse radiation. The amount of diffuse energy coming from different parts of the sky dome is often assumed to be uniform. This is not strictly true, even on the clearest days, and is definitely not true if there are any clouds. This non-uniform distribution is caused by many things, including ground reflection. It is also worth noting that the diffuse energy from a clear blue sky is partially polarized and that the amount of polarization varies with the direction from which the energy comes.

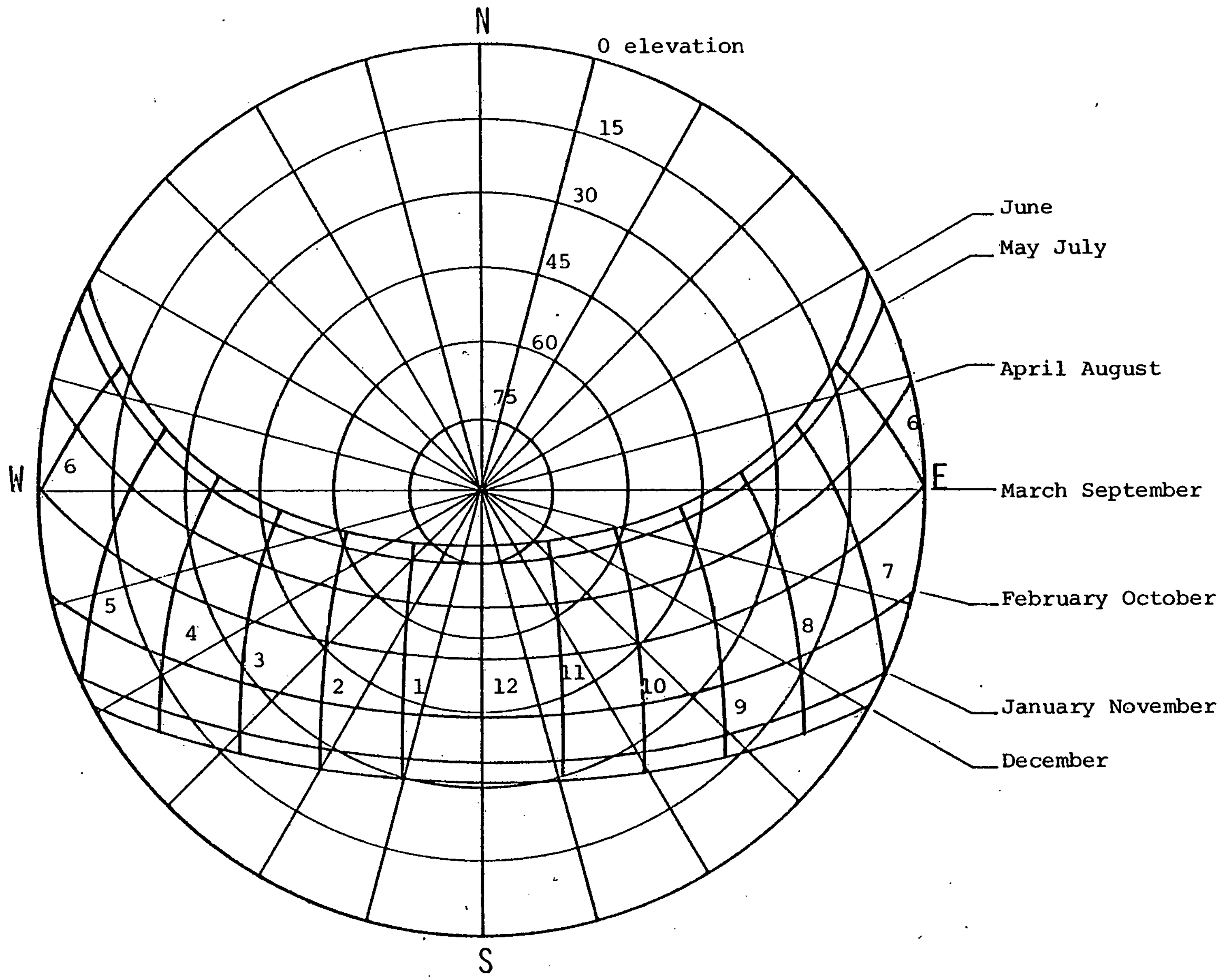

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Figure 5. Sunpath Diagram for 21st of each month.

DETECTORS FOR MEASUREMENT OF SOLAR RADIATION

Thermal Detectors

The thermal detectors use the incoming radiation to create a temperature difference in two elements of the detector. This is usually done by making one surface highly absorptive of the incoming radiation, and another surface highly reflective or otherwise structured so that its temperature is much less affected by the incoming radiation. Coatings are selected so that these coatings have a spectral characteristic as nearly flat as possible, e.g., like Figure 3. Because of the natural characteristics of the available materials, this nonselective characteristic is never perfect, but some materials are better than others.

A thermopile is part of the detector and has one side "hot" or thermally connected to the most absorbing surface, and the other side "cold". A thermopile is a series of thermocouples arranges so that the voltages add. An example is illustrated in Figure 6.

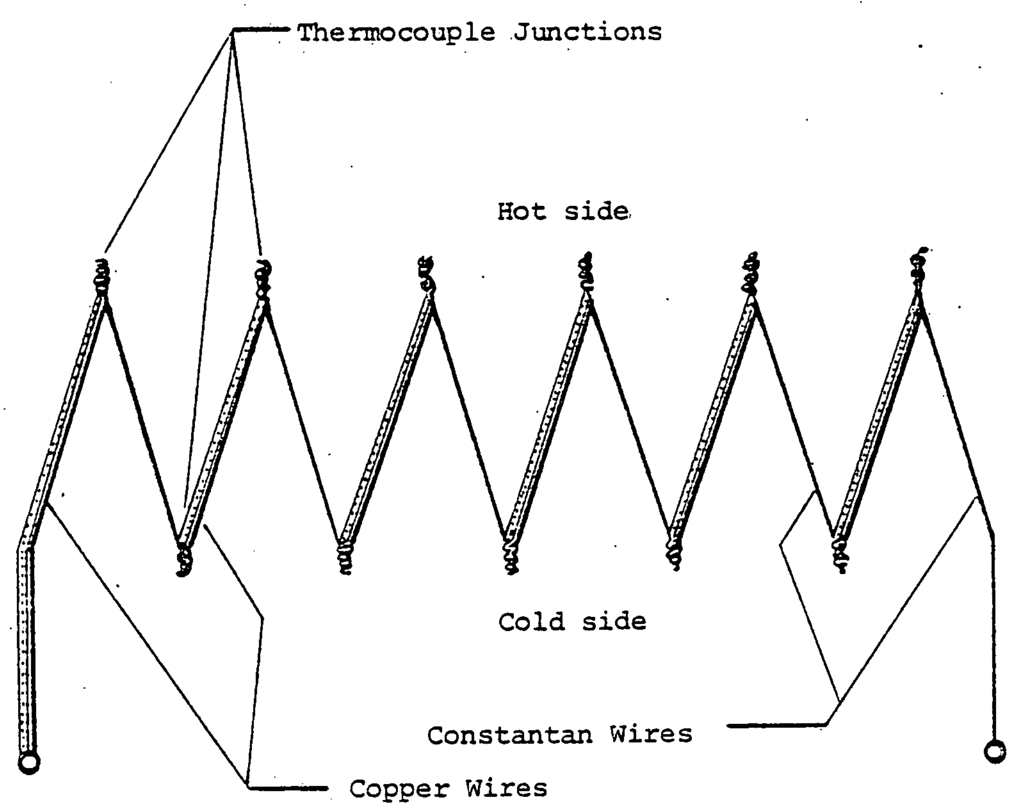


Figure 6. Illustration of Thermopile

The thermal detectors are popular because they are linear with intensity, rugged, can be built with very consistent results and are relatively simple to obtain known spectral characteristics with.

An important drawback to some thermal detectors is that they can be sensitive to tilt and thus can be used at only one tilt angle. This is particularly true with pyranometers which are normally only intended to be used in a horizontal position.

Photodetectors

The radiation striking a photodetector causes a change in the electrical properties of the detector. The major problem with photodetectors is that all have strong spectral characteristics. An important advantage is that these detectors can usually be used at any angle of tilt. There are three types of photodetectors commonly used to measure solar radiation. These are photovoltaic, photoconductive and photoemissive detectors.

Photovoltaic Detectors

The photovoltaic detector produces an electrical output which is a function of the solar radiation striking the cell. These devices convert the solar radiation directly into electrical energy.

There are many types of photovoltaic detectors. The most commonly used for solar radiation measurement is the silicon solar cell. This device produces a power output which is approximately linear with solar radiation incident on the cell. When shunted with a low resistance, of about 1 ohm, the voltage output of a cell is proportional to the solar radiation falling on the cell. Some specially made silicon detectors have the best linearity with intensity characteristics known and are thus used when it is important to measure relative intensity to a fraction of 1%.

Photoconductive Detectors

The electrical resistance of these devices is a function of the radiation input. These are among the least costly of all detectors, and some devices are reasonably linear over intensity changes of two or three orders of magnitude. These devices are often used because of their low cost or because they are easy to interface to control systems.

Photoemissive Detectors

These are often called photomultipliers. The photons from incoming radiation strike a cathode dislodging electrons which then are attracted to an anode dislodging more electrons. This last step is then repeated a number of times giving an electronic gain of many orders of magnitude. These are among the most sensitive detectors commonly available and are never used directly to measure solar radiation. They are used when the solar radiation has been highly filtered or otherwise reduced many orders of magnitude.

Pyroelectric Detectors

Radiation absorbed by the pyroelectric crystal is converted to heat, altering the crystal lattice spacing and producing a spontaneous electric polarization. The amount of voltage produced is proportional to the change of temperature and thus to the change of incoming radiation.

The most attractive features are the rapid response and the wide, relatively flat spectral sensitivity.

Pyroelectric detectors are normally considered laboratory devices. However, recently, a few have appeared in sophisticated field instruments for measuring solar radiation.

Pyroelectric detectors must be used in a circuit where the light beam is chopped in order to provide a rapidly changing temperature of the crystal.

INSTRUMENT GEOMETRY AND CONSTRUCTION

There are two basic types of solar radiation measuring instruments, the pyrheliometer and the pyranometer.

The pyrheliometer is intended for the measurement of only the direct beam energy per unit area on a surface normal to the solar beam. It resembles a small telescope which follows the solar disc across the sky. Because of the limitations of practical mechanical tracking mechanisms, the pyrheliometer accepts energy from an area of 5.7° diameter which is larger than the solar disc (about 0.5°).

The pyranometer is intended for the measurement of the total energy per unit area (direct and diffuse) falling on a horizontal surface. The pyranometer is normally fixed in a horizontal position. The sensitivity of a pyranometer is greatest for energy coming from the zenith and falls to zero for energy coming from the horizon. The variation in sensitivity should ideally be proportional to the cosine of the angle from the zenith. This proportional variation of sensitivity is termed "cosine response". Deviation from this desired response is termed "cosine error".

Pyrheliometers

The most commonly used pyrheliometer is the Eppley Normal Incidence Pyrheliometer (NIP).

It is necessary to eliminate the diffuse radiation of the sky from the measurement in order to measure the direct normal incidence radiation from the sun. This is done by mounting the sensor in the bottom of a long narrow collimation tube with field and aperture stops (holes) to limit the field of view (Figure 7).

The International Radiation Commission in 1956 defined the angles in collimation tubes as shown in Figure 8. (See Annex B of Appendix A)

The parameters for the Eppley NIP are: R = 10 mm, r = 2.75 mm, L = 200 mm, Zo = 2.86°, Zp = 2.08°, Z = 3.65°. The nominal diameter of the field of view is 2Zo = 5.7°.*

*Dorr Kimball, Training Handbook for Solar Radiation Measurements. A Southern California Edison internal document. (Eppley Laboratories notes that these are approximate values.)

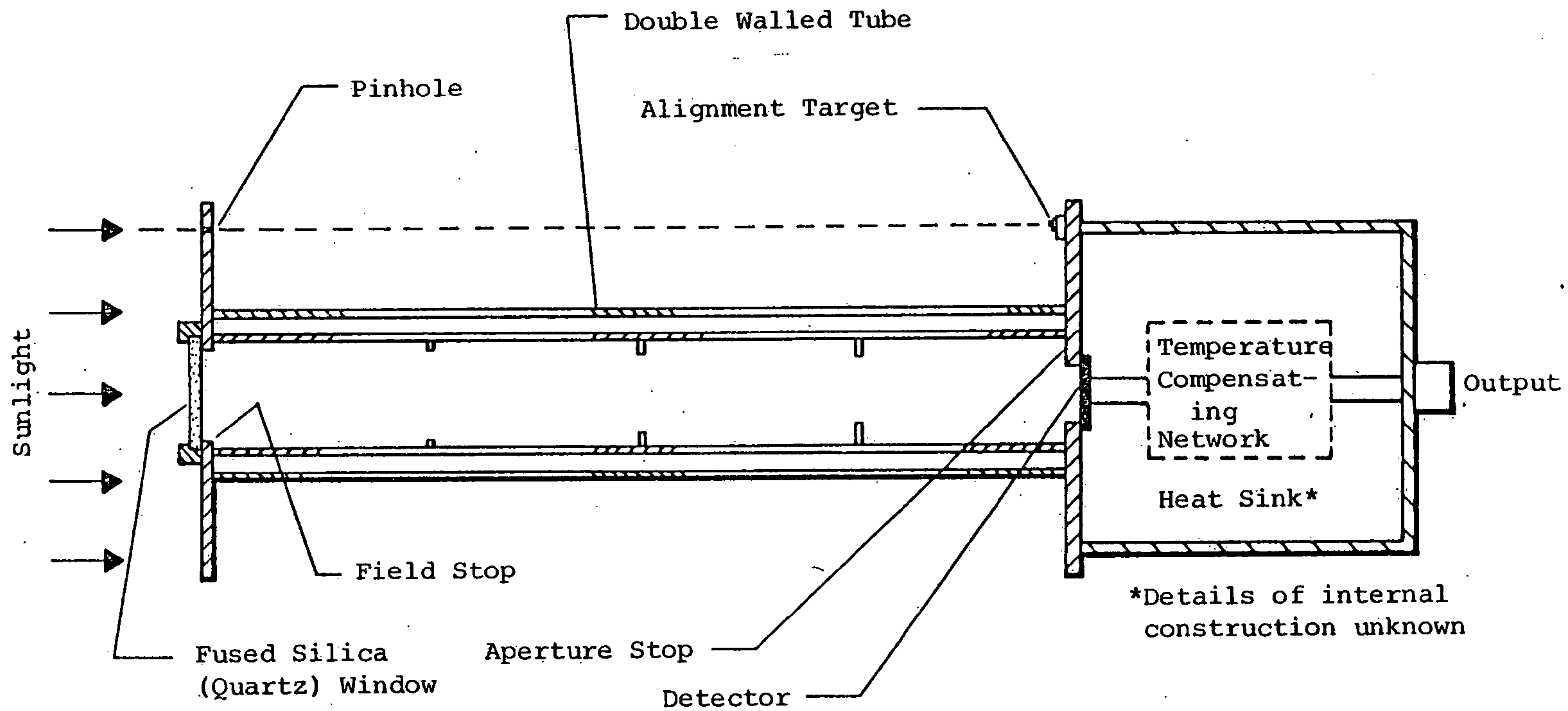
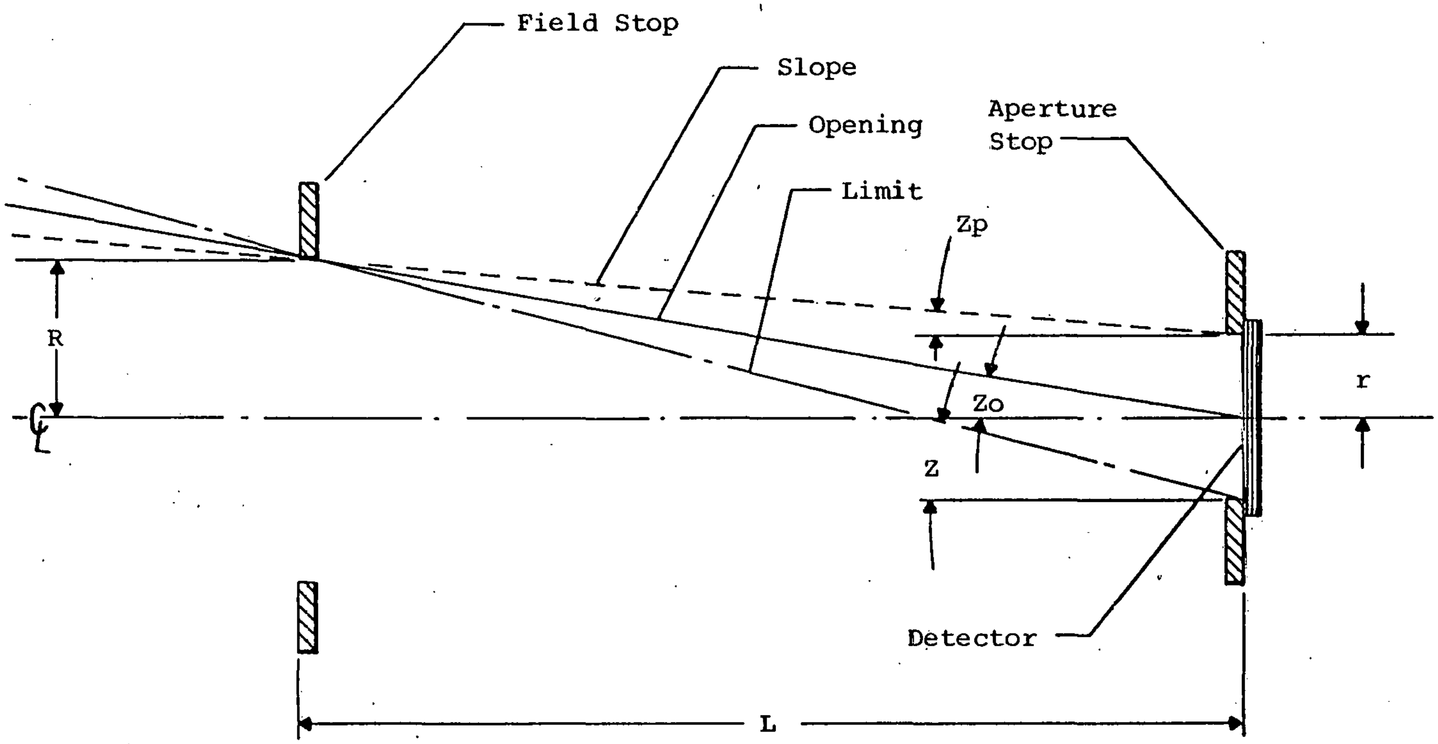


Figure 7. Approximate Construction of Eppley NIP.
(Adapted from Reference 3)



$$\text{Opening Angle} = Zo = \tan^{-1} \frac{R}{L}$$

$$\text{Slope Angle} = Zp = \tan^{-1} \frac{R-r}{L}$$

$$\text{Limit Angle} = Z = \tan^{-1} \frac{R+r}{L}$$

Figure 8. Definitions of Aperture Angles in collimation tube (Adapted from Reference 3)

Figure 9 shows to relative proportions the size of the sun (0.5°), the useful field of measurement (2Zp - 0.5° = 3.66°), the nominal field (2Zo = 5.7°), the extreme edge of the field (2Z = 7.30°) for the Eppley NIP. Between the useful field and the extreme field, the proportion of the circumsolar (around the sun) sky that is measured drops from 100% to 0%.

Measurements made at the Lawrence Berkeley Laboratory of the University of California with a very sophisticated custom-built scanning telescope indicate that on one clear day, the total circumsolar radiation out to a radius of 3° was 1.9% of the radiation from the sun, while on the clearest day measured, it was only 0.28%.

On hazy or smoggy days, it could be much larger and with clouds in front of the sun, it could be so large as to make a direct normal incidence reading almost meaningless.

Two pyrheliometers which do not have the same acceptance angles, as defined in Figure 8, will measure different amounts of the circumsolar radiation. If they agree on a very clear day, they may differ by several percent on a hazy or cloudy day. Because of this, calibrations of pyrheliometers are normally done only on very clear days.

Pyrheliometers - Tracking the Sun - Equatorial Mountings

If a pyrheliometer is to be used unattended, it must have some means to keep it pointed toward the sun. The method normally used is the equatorial mounting.

An equatorial mounting has two axes which are perpendicular to each other. The polar axis is inclined to the latitude of the observing site and adjusted on a true north-south line so that it points to the North celestial pole (in the Northern hemisphere). A synchronous motor with suitable gearing drives the polar axis at a rate of one revolution per day (24 hours) and a slip clutch allows setting for the time.

The polar axis carries the declination axis at right angles to it and the pyrheliometer is mounted at right angles to the declina-

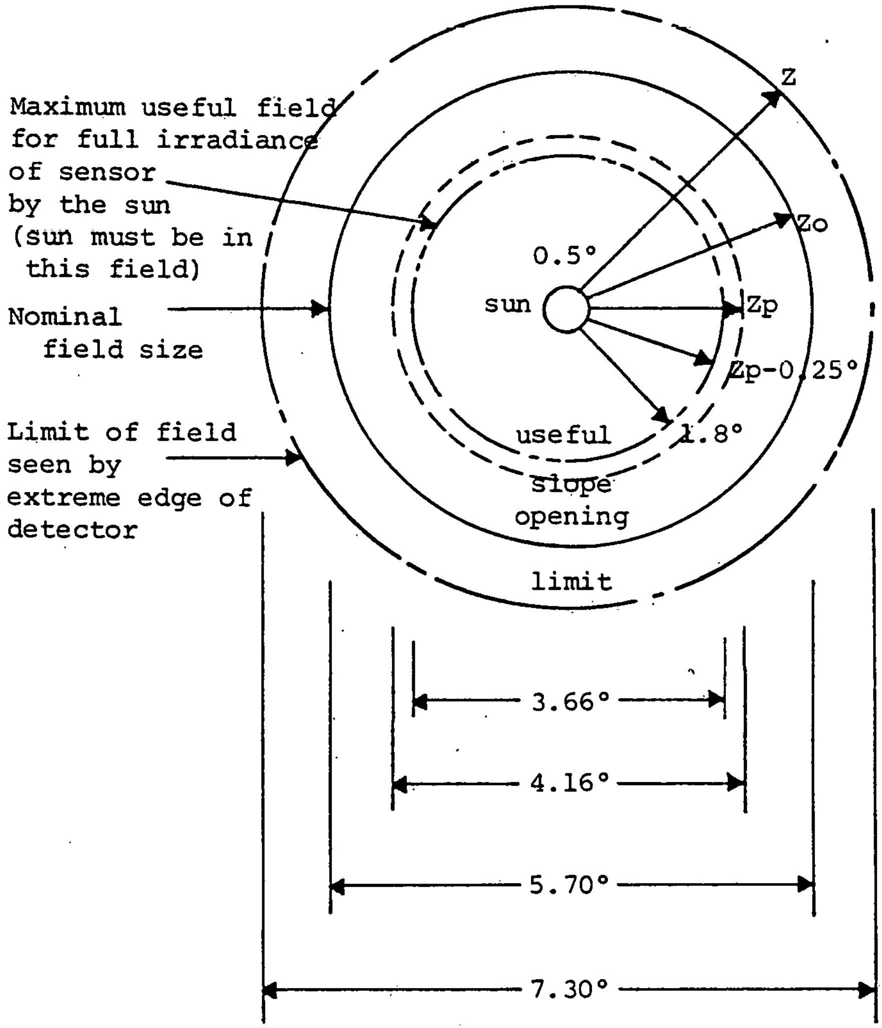


Figure 9. The circumsolar radiation field seen by the NIP Pyrheliometer Detector (adapted from Reference 3).

tion axis. The pyrheliometer is manually adjustable about the declination axis for any declination from +23-1/2° (north) to -23-1/2° (south).

Once the pyrheliometer is set to point to the sun by means of the slip clutch and the manual declination setting, it will continue to track the sun until changes in declination or in the equation of time cause it to slowly drift off. The pin hole and alignment target shown in Figure 7 are used to set the alignment.

Since the equatorial mounting of this type merely compensates for the rotation of the earth, and has no provision for automatic adjustment for the changing declination of the sun or the changes due to equation of time, it requires manual readjustment every few days. Since cleaning of the quartz window is also required at least once a week, there may be little advantage to designing a complicated automatic system to compensate for all the apparent motions of the sun.

The size of the useful field (Figure 9) is such as to allow a tracking error of approximately ±1.8° (2.08°-0.25°) before the measurement is affected. For proper operation of the equatorial, the polar axis should be adjusted to within 1/4° of the celestial pole.

Pyranometers

The detectors of pyranometers are flat and the pyranometers are mounted so that the sensor is exposed to the entire sky over a 180° angle in all directions. Three types of detectors are commonly used. These are the black thermal detectors used on the Eppley Precision Spectral Pyranometer (PSP) and the Spectrolab SR-75, and the black and white thermal detectors used on the Eppley Model 8-48 and the Schenk Star pyranometer. The third type of detector is the silicon photovoltaic cell mounted behind a diffusing filter, as in the Lambda or flat without a filter as in the Rho Sigma. The all-black thermal detectors are similar to those used in the pyrheliometers, and consist of plated multijunction thermopiles with the "hot" junctions in contact with the black disk and the "cold" junctions in thermal contact with a heat sink within the instrument. The black sensor's disk is covered with two hemispherical glass domes. A cross sectional diagram of the Eppley PSP is shown in Figure 10. According to Eppley, "The inner hemisphere of the PSP is employed to block infrared radiation interchange with the outer due to temperature differences. It also restricts thermal conduction through the air barrier between the two."

In the black and white sensors, the "hot" junctions are under the black segments and the "cold" junctions are under the white segments. Both the black and white segments absorb infrared, while the black absorbs the solar radiation and the white reflects it. This minimizes the effects due to heating and cooling of the dome so that only a single dome is required for this type.

Description of the Detectors Used in Both Eppley NIPs and PSPs

The detector consists of a black disk in thermal contact with the "hot" junctions of a multijunction thermopile. The corresponding cold junctions behind, but not in contact with the disk, are at approximately the same temperature as the base section of the pyrheliometer surrounding the back of the sensor. This base section has a large amount of metal which acts as a thermal heat sink and assumes a temperature close to the average ambient air temperature. It is painted white on the outside and shielded from the direct rays of the sun by a guard disc to minimize any warm-up by absorption of solar radiation.

The multijunction thermopile is constructed by forming a length on constantan wire into a small diameter helix similar to a coil spring or coiled lamp filament. Half of each turn of this helix is copper-plated by controlling the depth of the helix in the plating bath. (Figure 11)

Since the copper has only about 1/30 of the resistance of constantan for the same size wire, the copper-plated sections of the constantan wire act as if they were predominantly copper and a series of effective copper-constantan thermal junctions is formed.

The helix is oriented so that one set of junctions is brought into thermal contact with the black disk, while the other set becomes the reference junctions. This results in a very compact multijunction thermal detector.

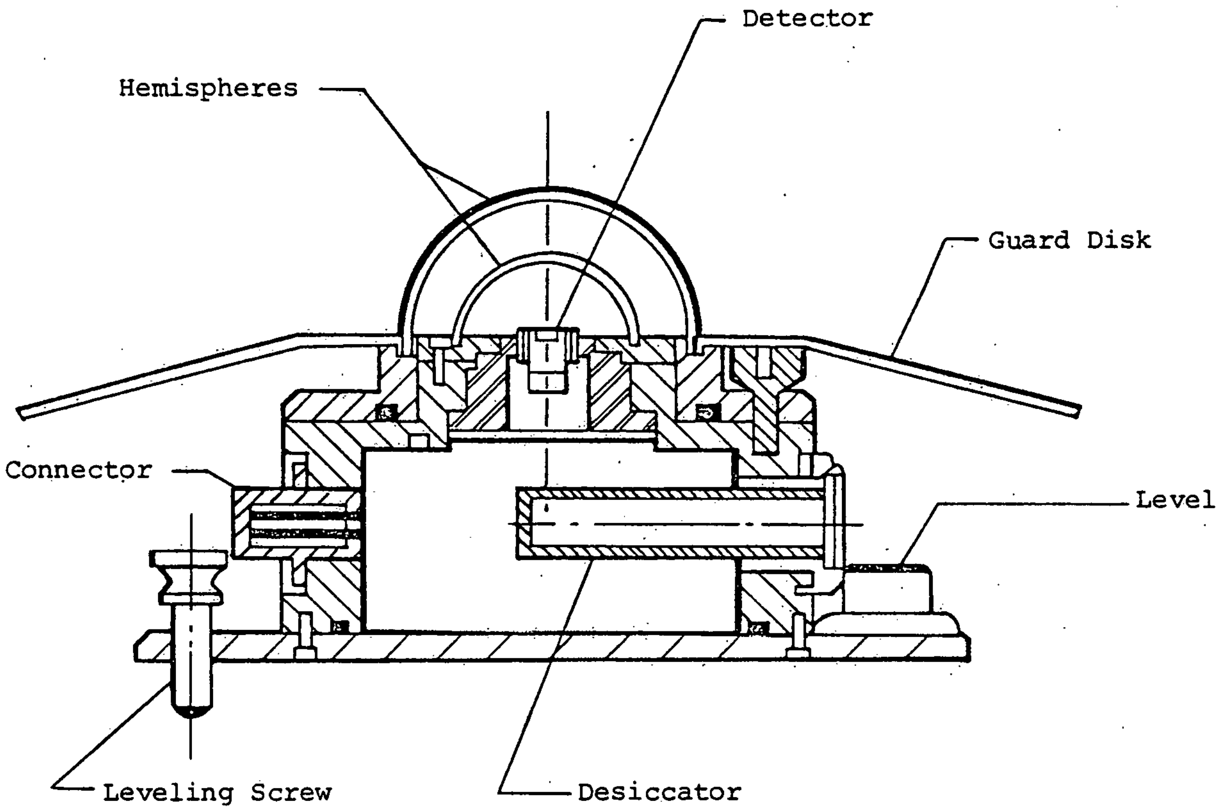


Figure 10. Cross Sectional Diagram of the Current Model (1978) of the Eppley Precision Spectral Pyranometer

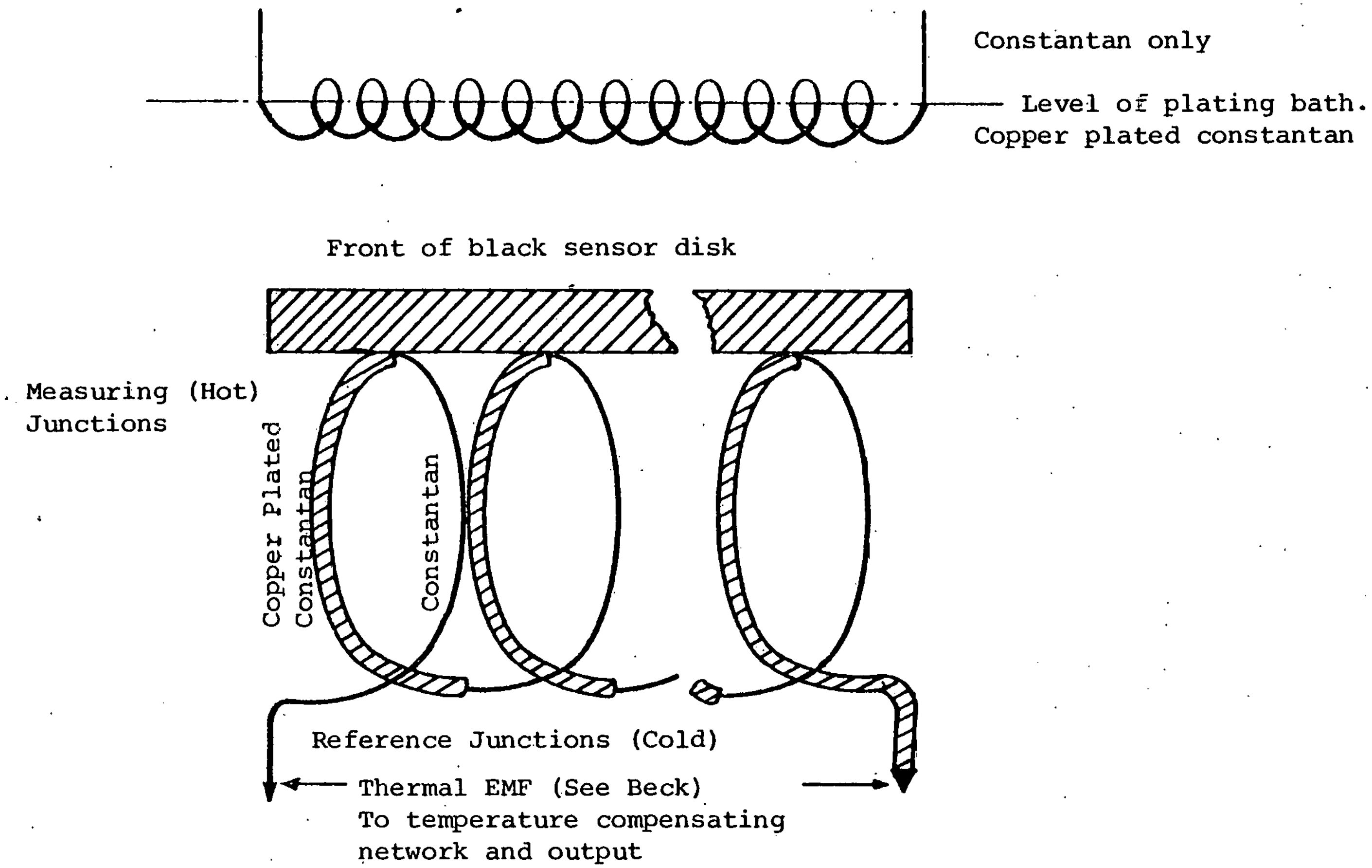


Figure 11. Multijunction thermocouple sensor (Adapted from Reference 3)

CALIBRATION ERRORS SOME EXAMPLES

This section describes some of the instrument-related errors which can occur.

Errors Due to Spectral Characteristics

These errors are perhaps the most subtle and difficult to deal with of all errors. All man-made materials are known to change their reflectivity or spectral characteristics after a period of exposure to the sun. The absorbing surfaces of pyranometers and pyrheliometers are no exception.

The old lampblack coatings used on early Eppley pyranometers actually changed so that these instruments became more sensitive with time. This effect is illustrated in Figure 12. The instrument sensitivity then later might decrease due to a degradation of the white coating.

The Parsons black paints used in Eppley pyranometers beginning around 1960 degraded slowly. It was later discovered that that was due to a heat-sealing process used on the instrument and not a problem inherent in the Parsons black paint. This problem has now been corrected.

The characteristic color of the light used when comparing two instruments will affect their relative readings if there is even a slight difference in their spectral sensitivity characteristics. Therefore, comparisons of two pyranometers under very clear skies may not agree with comparisons under cloudy skies by as much as 1% or 2% if, for example, one is relatively unused and another has been exposed outdoors for some time. This could occur even if the two instruments are of the same type and manufactured at the same time by the same manufacturer.

A notorious example of spectral errors occurred at the calibration facility of the U. S. National Weather Service (NWS). In the spring of 1956, Eppley began coating the black portion of the 180° pyranometer with Parsons black lacquer instead of lampblack. Until the late 1960's, these Parsons black sensors were calibrated by the

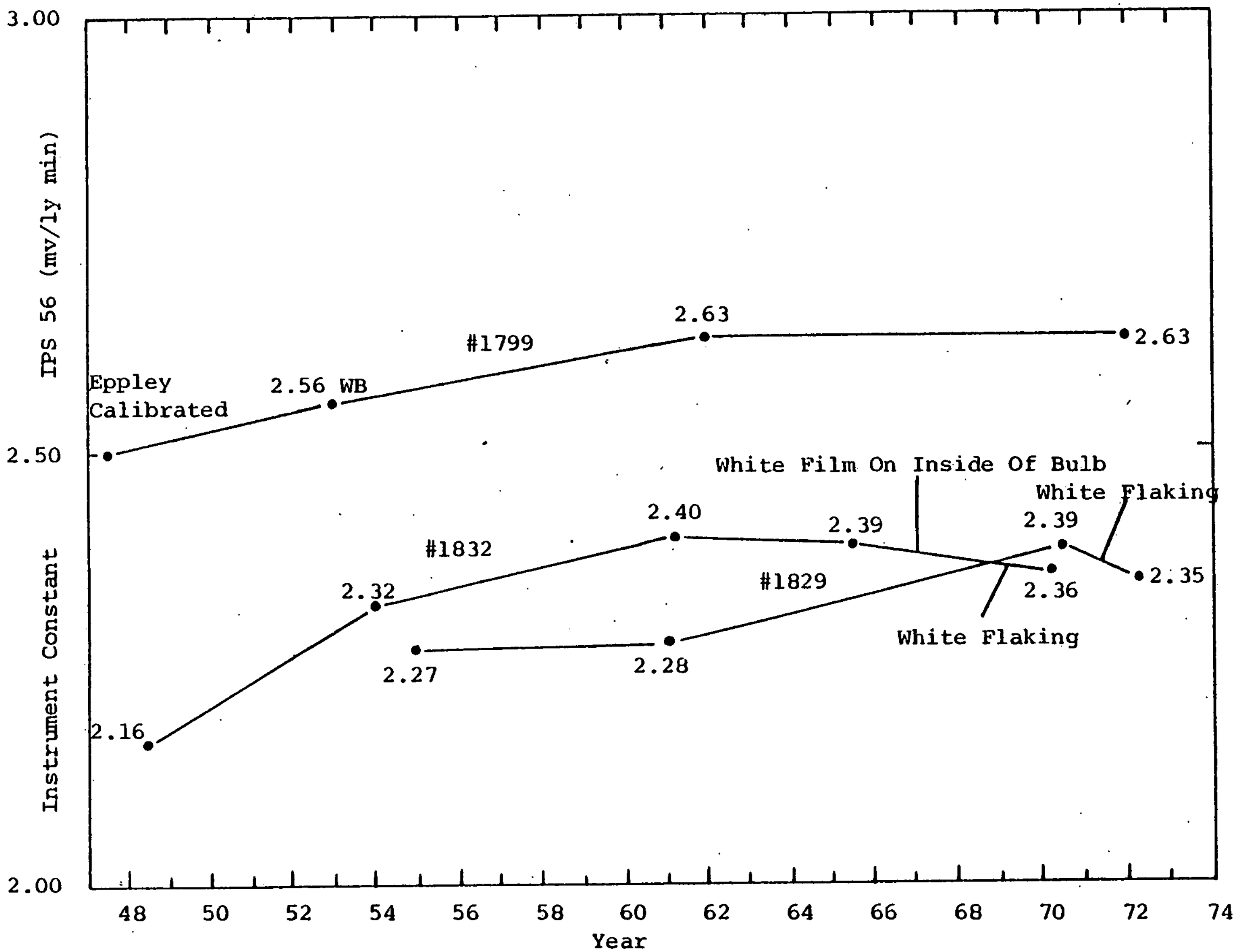


Figure 12. Example of Sensitivity Changes of Lampblack-Coated Sensors*

*Adapted from Michael R. Riches, "Engineering Connections to Solar Radiation Data" Appendix III of SOLMET Volume II-Final Report, TD-9724, published originally by Department of Energy, available from National Climatic Center, Federal Building, Asheville, NC 28802

NWS in the NWS integrating sphere using a tungsten light source comparing them against lampblack standards. This is the so-called "crossmatch" error. This crossmatch resulted in a calibration constant that was approximately 7% low. The data from these crossmatch instruments were approximately 7% high.

Many users desire data on the spectral content of the radiation. This type of measurement is often done with pyrheliometers with a filter wheel or pyranometers where the outer dome is itself a filter. After these filters have been in service for a few months, one often can see nonuniformities in them. Since the pyranometers are normally oriented in one direction, more fading on the side of filter nearest the sun would be expected. The precise measurement of the spectral content of solar radiation is a difficult task and requires careful adjustment of the data to compensate for filter changes.

Pyranometers and pyrheliometers used in the field for continuous measurements have glass windows* to protect the detector from the weather. While these windows are manufactured to transmit as much of the solar spectrum as possible, there is some absorption. When these instruments are compared with absolute-type instruments which have no windows, only openings, any nonuniformity of transmission of the glass windows across the solar spectrum could provide different calibration constants under differing light conditions.

A similar problem is that the spectral sensitivity of the detectors' black disk in absorbing radiation is nearly constant over a range from 0.3 to approximately 30 μm. However, the transmission of the window at the front of the pyrheliometer cuts off the transmission at approximately 3.0 μm.* The limiting of the spectral response is not a problem for solar radiation measurement as there is little solar radiation beyond 3.0 μm. However, there is some long wave terrestrial radiation reflected from the earth to the clouds and back to earth. When comparisons are made with standard pyrheliometers such as the Eppley NIP and absolute pyrheliometers such as the Kendall Mark VI which has no window to limit its spectral response, the latter will

*The Eppley NIP uses a crystal quartz window which transmits from below 0.3 to beyond 3.0 μm.

respond to some of this very long wave terrestrial radiation. These comparisons should, therefore, be made only on the very clearest driest days when that long wave terrestrial radiation is a minimum.

Pyranometers - Azimuth Errors

If the plane of the sensor is not level when the bubble level is centered, the accuracy will vary with orientation (azimuth) relative to the sun. This is a cosine type of error resulting from lack of level. A pyranometer can be tested for azimuth error by mounting it on a horizontal turntable that can be rotated relative to a fixed lamp at an angle of 60 or 75° from the vertical. Azimuth error is indicated by changes in the output voltage as the unit is rotated. Errors of nearly 1° have been found on some units.

In the case of the black and white (8-48) units, there are only six azimuths that can be used for this test using an artificial light source. To maintain equal amounts of black and white at the same distance from the light, the dividing line between black and white segments must always point toward the light.

Pyranometers - Cosine Error

Cosine errors are caused by a failure of the sensors' response to correspond with the theoretically-required cosine response to radiation at any angle. The black sensors of the Eppley PSP and the Spectrolab Sr-75 appear to reflect some of the radiation at low angles of incidence, and in general to produce less output at these angles than Lambert's Cosine Law requires.

These cosine errors are probably the largest type of error encountered with the pyranometers. Cosine errors are inherent in the geometrical and optical characteristics of a pyranometer which were fixed at the time of manufacture, and not subject to modification by the user.

Errors Due to Pyranometer Geometry

The following is excerpted from a paper by William C. Stevens.(1)

A series of tests* were conducted to investigate the effect of internal reflections on the response of an Eppley Model 8-48 Black and White Pyranometer. These tests were prompted by reports of internal reflection problems[1] and of large cosine response errors[2] with the 8-48. The results indicate that the azimuth response is not constant but has a cyclic variability related to the sun's azimuth angle with respect to the instrument's black and white detector. The 8-48 was illuminated with a narrow beam 1 mw helium-neon laser and the effects were visually observed. Ray diagrams for several of the dominant reflection modes are shown in Figure 13.

An Eppley PSP and the 8-48 were compared outside throughout the better part of a clear day. The differences in their outputs are illustrated in Figure 14. The effect of reflections is most pronounced for solar altitudes less than about 30° where the error reached 2% and increases rapidly for decreasing altitude angles. When individual errors for the 8-48 and PSP (as specified by the manufacturer) are considered, there appears to be reasonable agreement with the test data for solar altitudes less than 30°.

An 8-48 was placed on a turntable which rotated slowly. The output of the 8-48 and a PSP were recorded throughout much of the day. These results are illustrated in Figure 15.

Errors Due to Pyrheliometer Geometry

Pyrheliometers with different fields of view will obviously give different results depending upon the amount of energy in the circumsolar field viewed.

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*This work was sponsored by the U. S. Energy Research and Development Administration and by the New Mexico Energy Resources Board.

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(1) "The Effects of Internal Reflecting on the Cosine Response of an Eppely 8-48 Pyranometer." By W. C. Stevens, Energy R&D Section, Physical Science Laboratory, New Mexico State University, Las Cruces, NM 88003.

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[1] D. F. Grether, J. E. Nelson, M. Wahlig - Lawrence Berkeley Laboratory, University of California, Report No. 1, UCID-3705, NSF Grant AG-536, Measurement of Circumsolar Radiation.

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[2] B. J. Petterson of Sandia Laboratories - Personal discussion.

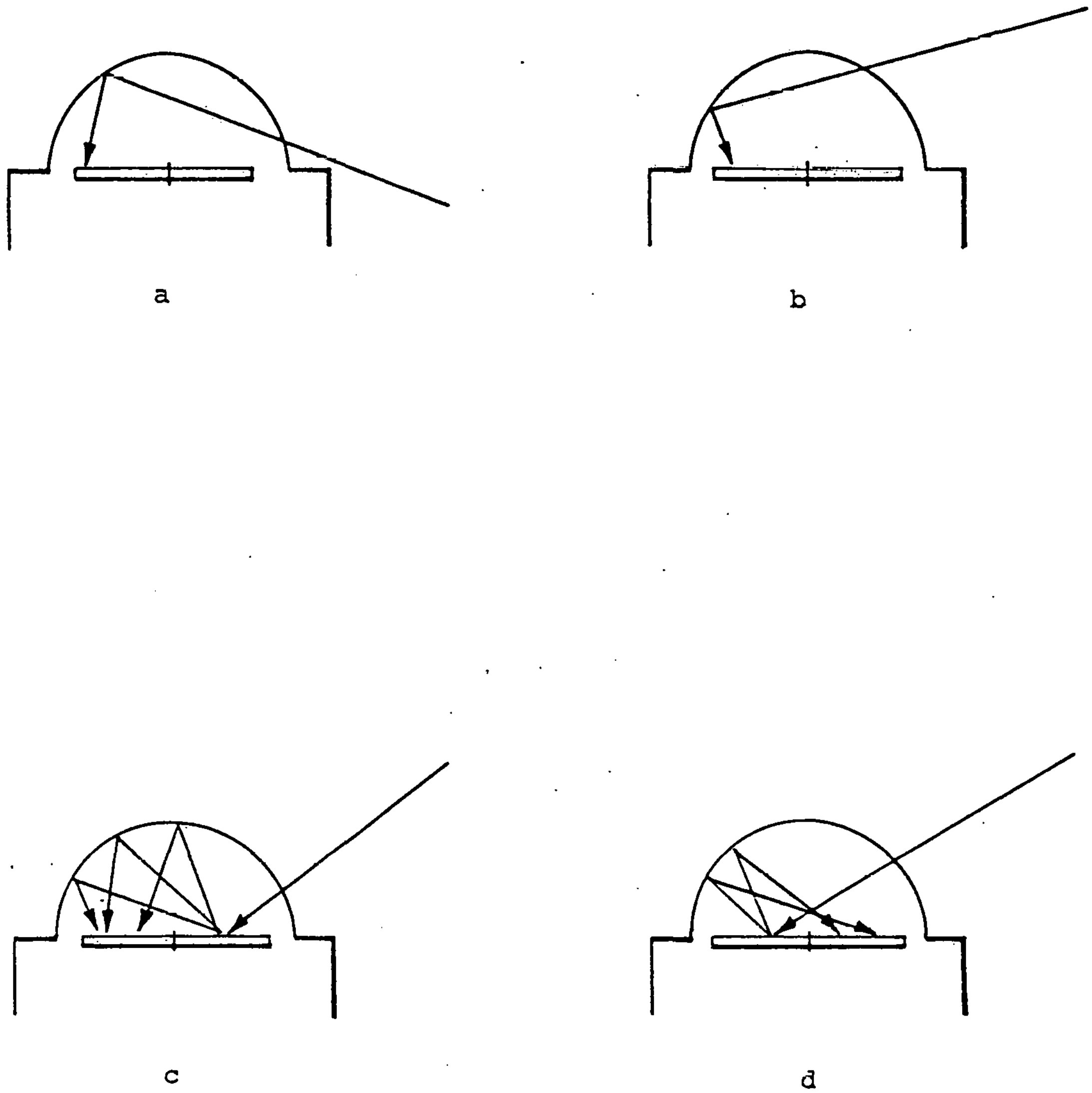

Figure 13. Typical 8-48 Internal Reflections

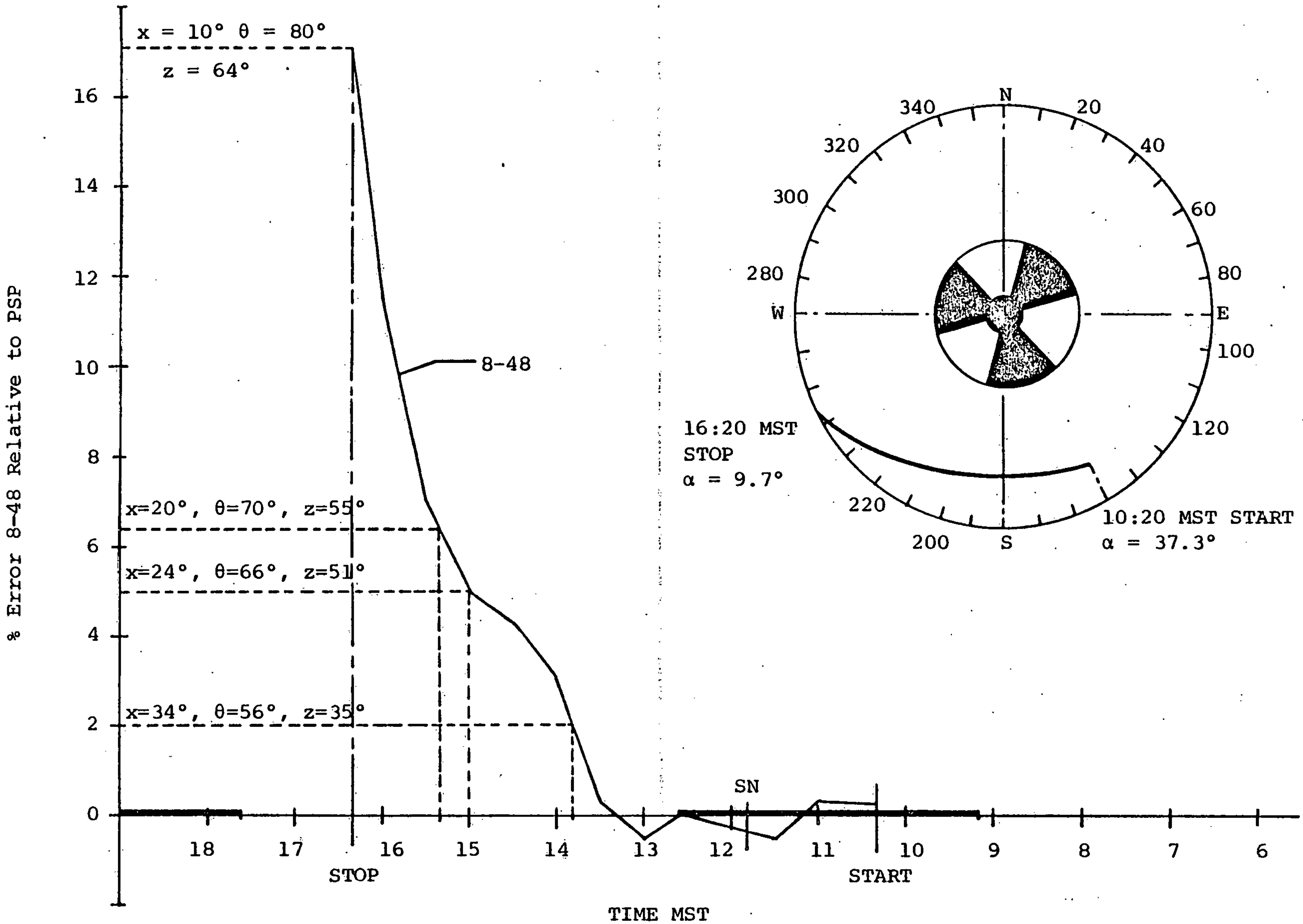

Figure 14. 8-48/PSP Comparison

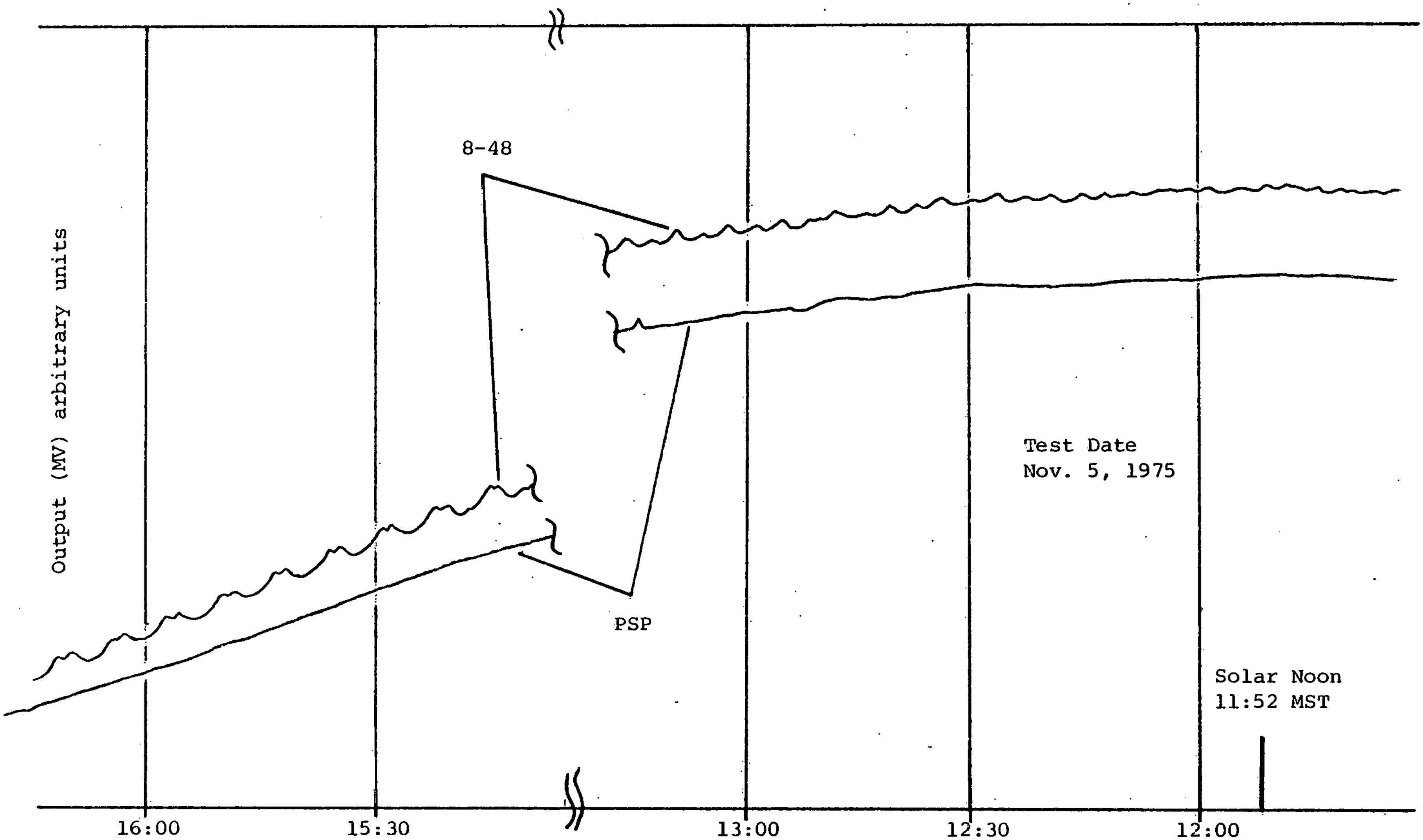

Figure 15. Comparison of 8-48 (on turntable) with PSP.

Precise alignment of two pyrheliometers during intercomparison can also be important, when there is a large amount of radiation from the circumsolar aureole, because a slight misalignment of one could cause it to accept less of the circumsolar energy even though the solar disc was well within the field of view.

Errors Due to Instrument Time Constant

The following is excerpted from a report prepared by Mr. Dorr Kimball of Southern California Edison (SCE) on the calibration of pyranometers and pyrheliometers. (Reference 2)

> The time constant (1/e for 63% output) is given as one second for the PSP, 1.6 seconds for the SR-75 and three to four seconds for the 8-48 (black and white). Approximately 99% of the reading is reached in 20 time constants or 20 seconds, 32 seconds, and 75 seconds, respectively.
>
> To study the effects of rapidly changing temperatures on these units, SCE placed one of each type in an environmental chamber in the dark at 25°C. All three units settled to an output within 1 or 2 microvolts of zero. The temperature was then raised to 50°C in three minutes. The response of the units was as follows: the PSP output rose to a peak of +455 microvolts in nine minutes and returned exponentially to zero in 90 minutes. The SR-75 output fell to -218 microvolts in 2 1/2 minutes and returned exponentially to zero in 12 1/2 minutes. The 8-48 (black and white) rose to a peak of +95 microvolts in five minutes and returned exponentially to zero in 60 minutes. While the pyranometers would not be subjected to sudden temperature changes of this magnitude in use, this experiment gives an idea of the effects of changing temperatures on the units. At a steady temperature, the temperature compensation circuits can compensate for different ambient temperatures, but during changing temperatures, there is a lag in the temperature compensation.
>
> Both the Eppley PSP and the Spectrolab SR-75 have shields to shade the body of the unit (heat sink) from the solar radiation. This is not necessary in the Eppley 8-48 (black and white) unit since body of the unit is not used as a heat sink or reference junction, this function being performed by the white sectors.
>
> The time constant for a 1/e signal (to approximately 63%) for the Eppley NIP is one second. It takes approximately 20 seconds to reach 99% of its final reading. This is the time constant of the small black disk which heats the measuring junctions of the thermocouples. The time constant of the body of the unit representing the heat sink and the cold junction temperature is much larger, and may lag an hour or more behind the changes

in external ambient temperature. The output voltage of the thermopile is proportional to the difference in temperature between the black disk and the heat sink.

Heat can be transmitted in three ways: by electromagetic radiation, by conduction in solids, and by convection in gases and liquids. In the pyrheliometer, all parts essentially respond the same to the ambient air temperature by convection and only the black disk is exposed to the solar radiation. Thus, the output voltage is essentially proportional to the solar radiation. Under constant ambient temperature conditions, the black disk sensor and the heat sink are affected equally. However, under changing ambient conditions, the larger mass of the heat sink causes it to lag behind the sensor in responding to change.

Under actual conditions of use where the ambient temperature changes are gradual, the errors caused by the different time constants of the sensor and its reference junction are not large. The temperature compensation circuits compensate for the effects of different ambient temperatures within manufacturer's specifications.

However, when the pyrheliometer is subjected to a more abrupt change in ambient temperature, temporary changes in the accuracy of its output can amount to several percent. Eppley NIP No. 13384E6 was placed in an environmental control chamber in the dark at 25°C. Its output was 0 microvolts. The temperature of the chamber was then raised to 47°C in a few minutes. In ten minutes, the output of the unit was 125 microvolts. It required approximately two hours at this temperature for the output voltage to return exponentially to zero. This gives an idea of what might be called the secondary or reference junction time constant. This can cause errors when calibrating one pyrheliometer against another if sufficient time is not allowed for stabilization after a change in ambient temperature. For example, a NIP used as a standard might be taken from a warm room at 72°F to an outside installation with an installed NIP which had reached thermal equilibrium with a 40°F ambient. Anywhere from 30 minutes to two hours might be required for the standard to reach thermal equilibrium with the new ambient if errors are to be avoided in the calibration.

Tests in the laboratory with tungsten light sources involve heat (infrared radiation) which can cause many calibration problems which require attention if large errors are to be avoided. Fans can be used to provide a rapid change of air between the tungsten light source and the pyrheliometer, and so reduce transmission of heat to the unit by convection. Aluminum shields can limit the beam to reduce heating by infrared radiation.

Because of the individual temperature compensating networks in the NIP, different units may react differently to sudden changes in ambient temperature. If a unit exposed to the sun or to tungsten light radiation is capped with a light-tight aluminum cap, it will often indicate an output of +60 μv or more after 20 time constants (20 seconds for the NIP), and may take 10-30 minutes to reach zero. In some cases, the output may then go negative, indicating that the temperature of the sensor has fallen below the temperature of the heat sink or reference junctions. The interchanges of heat between the heat sink, the sensor, and the thermistor and resistor temperature compensating network are complex and seem to vary from unit to unit.

Errors Due to Nonstandard Mounting

Pyrheliometers are designed to track the sun. The body of the instrument is normally designed to be shaded from the direct rays of the sun. Nonuniform heating or cooling of the body of the pyranometer due to reflected rays of the sun or other means can cause unpredictable instrument performance.

Pyranometers are designed to be mounted in a horizontal position and are normally calibrated in that position. There is currently a demand for instruments which can be used at a tilted nonhorizontal position and in a vertical position, both in measuring the performance of solar collectors and in predicting the insolation available at a given tilt.

It has been shown that the calibration of pyranometers with thermal sensors does vary with tilt. Some earlier versions of the Eppley Model 8-48 had errors of nearly 5%. This is said to have been due to convection currents inside the instrument. More recent versions of the Eppley Model 8-48 have a modification to minimize this effect.

Photovoltaic sensors should not show any effects due to tilting. However, it must be kept in mind that the spectral character of the illumination viewed by a pyranometer in the sunlight will almost always change when the instrument is tilted because some of the light viewed is reflected from different objects and different parts of the sky.

Pyranometers are sometimes used along with an artificial horizon, the nonuniformities in the response of the detector across the surface could cause unexpected performances. Figure 16 illustrates the shape of the response which might be expected from an Eppley PSP, due to the location of the thermopile in the detector.

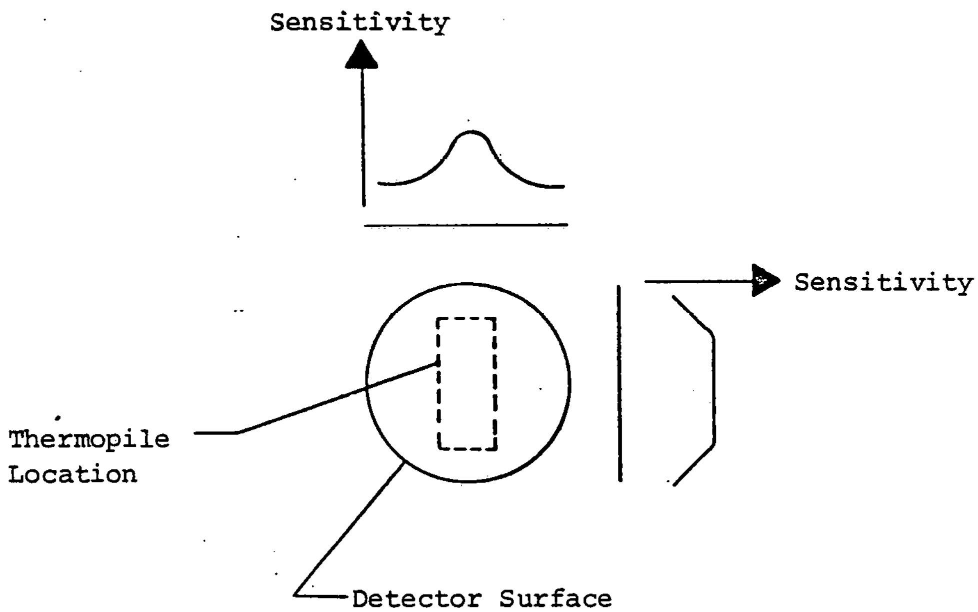

Figure 16. Non-uniform Sensitivity Expected from a Thermopile Sensor Such as the PSP

Part II. CALIBRATION: DEFINITIONS, METHODS AND PROCEDURES

INTRODUCTION

The quality of the calibrations depends primarily upon the knowledge and experience of the experimenter. While some calibrations presented in this section may appear simple and others complex, none can be accomplished satisfactorily without a thorough knowledge of the instruments. This section of the report is not a "cookbook." The procedures described here require additional planning.

Before attempting any calibrations the user should carefully define his objectives in making the measurements for which the instrument is being calibrated. A precise statement of the required measurements will define the type of calibration required and the accuracies required. Many calibration steps may be totally unnecessary.

The use of statistics is not described in this report. The number of observations required in any given experiment will depend upon the precision of each individual observation, the final result required, the noise and errors present. Many good books on statistics are available.

Definition of Calibration

Each measuring instrument has specific characteristics and when the instrument is used to measure something these characteristics affect the measurement result. A complete knowledge of these characteristics and their interaction with the measurement process is necessary in order to precisely define the phenomenon which is being measured. Sometimes it is said that this defines the "measurement".

The definition of instrument calibration used here is:

Calibration is the determination of all the important characteristics of an instrument which are related to a particular measurement.

Note that calibration is related to the measurement to be taken as well as the instrument itself. A pyranometer which is used only under clear skies in a horizontal position will require a different kind of calibration from one which is to be used at an angle under all types of weather.

We will in the following sections identify the important characteristics of each instrument which are most commonly needed and define with mathematical precision an "idealized instrument". This definition of an idealized instrument can be used as a basis from which to implement calibration procedures and from which to specify important instrument characteristics.

Common Instrument Characteristics

The following definitions are imprecise, but are presented here to serve as a frame of reference for the later more precise definitions. Some of the instrument characteristics commonly identified are:

a) Calibration constant - the relationship between the intensity of incoming radiation sensed by the instrument and the signal output. This is sometimes called sensitivity.

b) Angular or geometric response - the variation in instrument sensitivity with the direction of incoming radiation.

c) Linearity - the constancy of the "calibration constant" with changes in intensity or amount of incoming radiation.

d) Stability - the constancy of a given characteristic (usually the calibration constant) with variations in other parameters (usually referred to time or instrument aging).

e) Spectral response - the sensitivity of the instrument to different wavelengths of radiation, or the variation in the calibration constant with different wavelengths of radiation.

f) Temperature stability - the variation of calibration constant and other characteristics with a change in ambient (drybulb) temperature.

There are a number of other characteristics which can be considered such as sensitivity to wind; and, or sensitivity to dirt on the optical window. Each use of an instrument has its own requirements for calibration and the user must judge for himself which instrument characteristics are important enough to merit individual analysis.

Interactions Between Characteristics

It is often assumed that each instrument characteristic can be identified and measured separately and then the resulting performance (or error) is a linear combination (total error is the sum of individual errors) of the individual characteristics. In fact the interaction between individual characteristics can be quite significant.

In mathematical terms one could state these as, the total error is the sum of the individual errors, (for a pyranometer as an example):

$$E_t = E_{azm} + E_{cos} + E_{spec}$$

where: E_t = total error in a particular measurement,

E_{azm} = error due to variations in the azmuth orientation,

E_{cos} = error due to variations from (elevation) cosine response,

E_{spec} = error due to nonuniform spectral response, or as the total error is a sum of the individual errors and the interactions between these instrument characteristics, for example:

$$E_t = E_{azm} + E_{cos} + E_{spec} + E_{azm\ cos} + E_{azm\ spec} + E_{cos\ spec} + E_{azm\ cos\ spec}$$

Where: $E_{azm\ cos}$ = error due to interaction between the solar elevation and the azmuth of the sun with respect to the instrument,

$E_{azm\ spec}$ = error due to interactions between the azimuth angle of radiation and the color of the radiation,

$E_{cos\ spec}$ = error due to interactions between the elevation angle of the radiation and the color of the radiation, and

$E_{azm\ cos\ spec}$ = error due to interactions between all three components.

As an illustration of these characteristics refer to the previous section entitled Errors Due to Pyranometer Geometry, and Figures 13, 14 and 15. Figure 13 illustrates internal reflection modes which are potential contributions to both azmuth errors and cosine (elevation) errors depending on the angle of the incoming ray and whether it first strikes a light or dark wedge. Also since the dome is not infinitely thin but has a thickness, the rays which do not pass through the dome in a path which is directly normal to the surface could experience dispersion of the spectrum as in a prism.

Figure 14 illustrates the fact that both E_{azm} and E_{cos} exist and are significant.

Figure 15 clearly illustrates the interaction term $E_{azm\ cos}$.

The terms E_{spec}, $E_{azm\ spec}$, $E_{cos\ spec}$, and $E_{azm\ cos\ spec}$ are not illustrated, and it is not obvious whether they are significant or not. They must be measured to determine their significance.

The foregoing examples are given to illustrate the complexity of possible interactions which should be considered during instrument calibration. Since there are in reality many more possible terms than illustrated in the example, calibration can be an extremely complex process. Considerable judgement must be exercised when identifying the important terms.

CALIBRATION OF PYRANOMETERS

A pyranometer was originally intended to measure the solar radiation falling on a horizontal surface.

Pyranometer: The Idealized Instrument

The idealized pyranometer is defined as having the following characteristics:

Spectral Response and Linearity only:

$$V = KI_x \quad \text{for } 0.2\mu m \leq x \leq 3.0\mu m$$

$$V = 0 \quad \text{for } x < 0.2\mu m \text{ or } x > 3\mu m$$

Geometric Response only:

$$V = K\cos(a) \quad \text{for } a \leq +90°$$

$$V = 0 \quad \text{for } a > 90°$$

where: V is the output in volts

K is the "calibration constant"

I_x is the radiation intensity at wavelength x

a is the angle of the incoming solar radiation from the normal (zenith) of the instrument (this is 90° - solar elevation (α) for a horizontal instrument and direct beam radiation).

The above holds for all temperatures 0°K to ∞ for any environmental condition wind, rain, etc, for any electrical load applied to the output terminals of the instrument, for any angle of tilt, and for all azmuthal angles.

The output of the instrument is:

$$V_o = \int_0^{90} \int_0^{360} \int_{0.2}^{3.0} KI_2 \, Cos\,(a) \, dI_x \, d_{azm} \, d_a$$

For our idealized instrument the "calibration constant" K is a true constant and could be placed before the integrals.

K is shown inside the integrals to emphasize the fact that it is not a true constant for an actual instrument. The purpose of calibration is to identify the true functional relationship(s) between

K and a variety of other variables including I_x, a, azm, temperature, wind, tilt angle, load etc.

Pyranometers: The Factors Normally Evaluated

The following factors are commonly considered when calibrating pyranometers:

a) The calibration constant K is determined at a nominal 25°C temperature (or sometimes other temperatures).

b) The range of variation of K with a given range of temperature, (usually +40°C to -40°C).

c) The dynamic response of the instrument, (usually specified as a time constant by measuring the response to a step function in illumination and assuming an exponential shape to the functional change).

The following factors are sometimes evaluated but much less often than the foregoing:

a) The cosine response - the deviation of the instruments response from the idealized instrument as a function of a.

b) The tilt angle response - the variation of K as the instrument is tilted from the horizontal position to some other position.

c) Direction of maximum response - if different from the zenith when the instrument is leveled according to the indicator on the instrument.

d) Spectral response - this is sometimes done by measuring the characteristics of individual components, the dome, black paint etc and then by computing the combined response.

e) The linearity - K as a function of the intensity of solar radiation.

Pyranometer: Potentially Important Factors Seldom Evaluated

The following factors are seldom evaluated for a variety of reasons:

a) The interactions due to two or more of any of the causes discussed here. Justification for this may be that the interaction terms due to two or more factors are small (this has not been shown), or that the information would not be used even if it were known.

b) The effects of wind on the instrument. This is a difficult experiment as the effects may depend to a large degree on ambient temperature, direction of the wind with respect to the sun, the intensity of the solar radiation, and humidity and other effective sky temperature factors, all of which should be well known.

c) Effects of the electrical impedance applied to the output terminals of the instrument on K and other factors.

d) The sensitivity of the instrument in conjunction with its associated load to electromagnetic radiation in the form of radio waves, or microwaves. This can interact strongly with the impedance in c) above.

e) Factors due to the effective sky temperature. The effective sky temperature can vary from +20°C to -40°C under conditions where pyranometers are commonly used. This variability could affect the radiation balance of the dome and other parts of the instrument. An illustration of the fact that some pyranometers respond to outgoing radiation is the fact that they show a small negative voltage output during the nighttime hours.

f) Formation of images or nonuniform illumination of detector due to optical properties of the domes. The dome or domes because of their curvature have the potential for image formation, either by refraction or reflection from the interior surfaces. This is probably the most serious drawback of the wedge shaped models. This is illustrated in Figure 13.

Pyranometer: Procedures for Calibration

The procedures given in this section include both commonly used procedures, and some which have never been tried. The user of these procedures must judge for himself which are appropriate for his instrument and the measures he wishes to make with that instrument.

a) Determination of the Calibration Constant - Transfer From Another Pyranometer In Sunlight.

Two (or more) pyranometers are mounted in a horizontal position, side by side, separated by at least 30cm and preferably 1 meter, so that each views the same sky dome. The instrument is oriented so that the bubble level is closest to the nearest pole (north pole in northern hemisphere, south pole in the southern hemisphere). Preferably there are no obstructions on the entire horizon. One (or more) of the pyranometers is the standard. The output of each instrument is then connected to a specified load, and the voltages are compared. The ratios of the calibration constants are the same as the ratios of the voltages output. The instruments should be allowed to stabilize in the environment for at least one hour before taking any data.

It is often desirable to integrate or average the outputs over a period of time and to then compute the calibration constants on the basis of these averages. This reduces the errors due to differences in dynamic response, sun angle and other factors which may average out in a number of readings.

There are at least two different philosophies regarding the type of weather conditions under which this calibration should be made. The first is that the conditions should be such that they are as nearly reproducible as possible. Thus calibrations should be done only on the clearest days near noon, and at a time of the year when the sun is relatively high in the sky. The second philosophy is that the instruments should be calibrated at conditions which are representative of those under which they are to be used. Thus averages of the data are made over much of the day and data are taken for days which include a variety of weather conditions.

Each of these methods has its benefits. The first would be better for determining long term drift of the calibration, and for providing a precise calibration constant. The second might be better for transferring calibration between two instruments which had slightly different spectral response but were to be used to make the same all-weather measures.

b) Determination of the Calibration Constant - Transfer From Another Pyranometer In Laboratory.

This procedure should only be used where the transfer is between instruments of the same manufacturer and model, and which use the same optical surfaces and coatings. This calibration is performed in a specially designed room called an "integrating sphere". Such a room is designed so that illumination flux levels at all points where the instruments are located are equal.

The design and construction of such a room are beyond the scope of this report, but special problems must be considered including cooling the surface of the sphere and maintaining constant air temperatures. These can be difficult because of the high flux levels required. Flux levels should be close to those experienced on a sunny day out of doors.

In the use of this method, instruments are placed in the sphere, and the illumination is turned on. Conditions are allowed to stabilize and then the data are collected which determine the calibration constants.

This method is most useful in a manufacturing facility or very cloudy climate, where number of calibrations is important and schedules cannot be stretched to accommodate the weather unpredictability.

The spectral content of the illumination in the sphere is not the same as sunlight.

The proper use of this method requires a lot of experience.

c) Determination of Calibration Constant - Transfer From A Pyrheliometer.

This step is necessary to initially obtain and to maintain a calibrated pyranometer. There are no standards of radiation which are adequate for calibrating pyranometers, because of their wide angle of sensitivity. The best currently available standards are embodied in the so-called "absolute instruments", discussed in a following section of this report. These instruments measure the radiation over only a small solid angle 5.7° and thus a special procedure is required to transfer the calibration to a pyranometer.

The transfer of calibration from a pyrheliometer to a pyranometer should always be done in a climate and under sky conditions which have strongest beam solar radiation and a minimum of circumsolar radiation. Figure 17 shows two examples of measured circumsolar radiation. Note how the intensity at the Albuquerque site falls by over 3 orders of magnitude within 1/2 degree of the center of the solar disc. Referring to Figure 9 in the previous chapter, which illustrates the field of view of the Eppley NIP, one can see that errors in pointing of or tracking of the pyrheliometer, or placing of the shading disc, will have much less effect in a weather situation similar to that shown on the right of Figure 17 than in the situation shown on the left.

There are two basic methods for transferring calibration from a narrow field of view instrument (pyrheliometer) to a wide field of view instrument (pyranometer). These are often called:

- the sun and shade method, and
- the collimation tube method.

Each of these can be done in two ways:

- the pyranometer mounted horizontally,
- the pyranometer tracking and normal to the incoming beam radiation.

The pyranometer senses the radiation coming from an entire hemisphere of the sky dome. We call this the total radiation (I_T). The pyrheliometer senses only the radiation coming from an area immediately adjacent to the solar disc. We call this the beam radiation (I_b). The diffuse radiation (I_d) is commonly defined as all the total radiation except for the beam radiation.

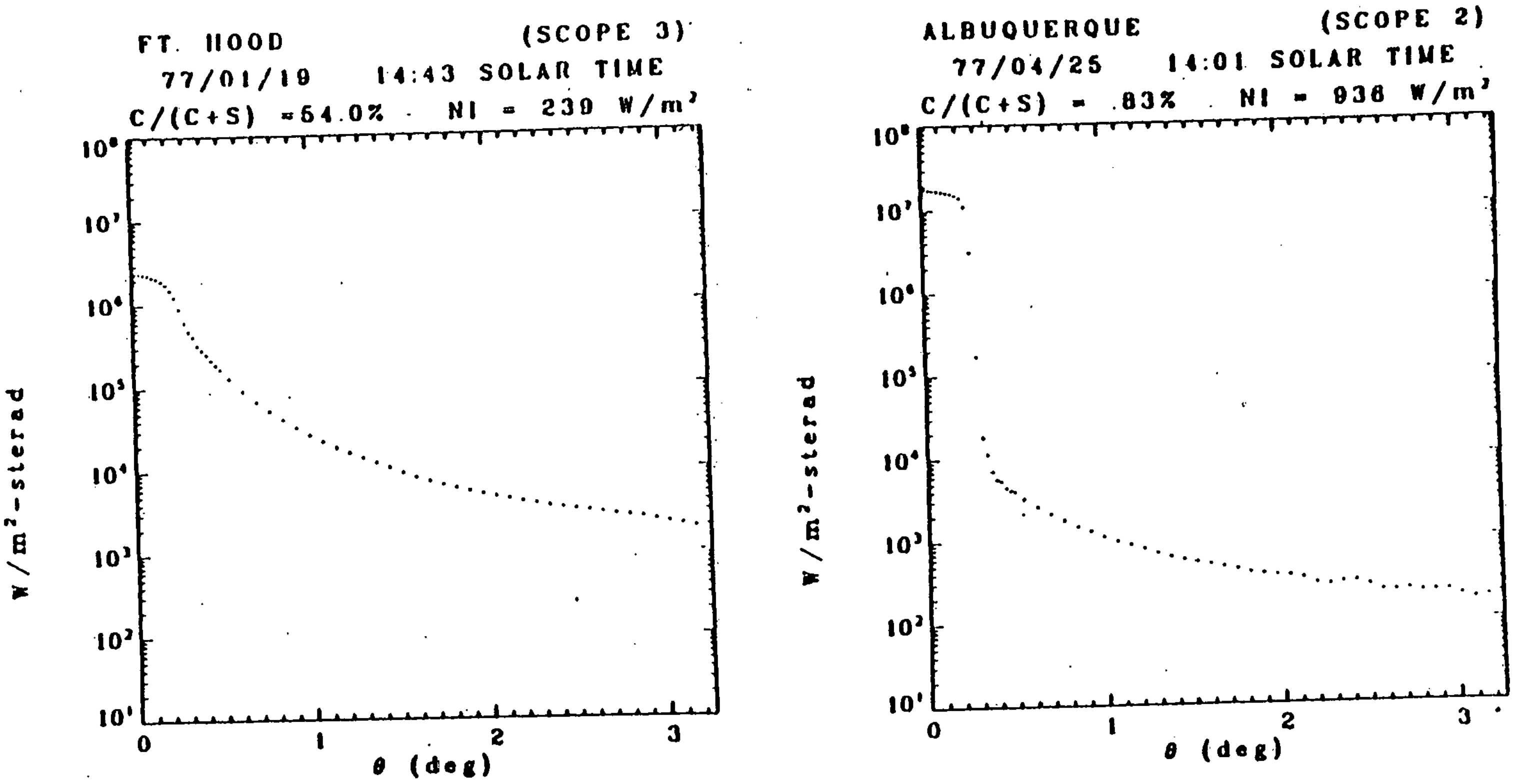

Figure 17. Examples of circumsolar radiation, Image intensity vs. distance from center of solar disc.

(Courtesy of Lawrence Berkeley Laboratories, Reference 5)

$$I_d = I_T - I_b$$

In the sun and shade method I_d and I_T are measured with the pyranometer being calibrated and I_b is measured with the pyrheliometer. While in the collimation tube method only I_b is measured.

1) <u>The Sun and Shade Method</u>

Using the sun and shade method a disc, which obscures a portion of the sky equal to the same solid angle seen by the pyrheliometer (5.6° dia.) is used.* The disc is alternately placed between the sun and the pyranometer, and removed. The difference of these two readings represents the direct beam radiation, as measured by the pyrheliometer. If the pyranometer is mounted in the horizontal position, the difference must be multiplied by the cosine of the solar zenith distance to obtain the proper value.

The sun and shade method is illustrated in Figure 18.

It is always a good practice when performing calibrations on one pyranometer, to have a second pyranometer measuring the total or preferably the diffuse radiation during the experiment, to assure that changes in the levels of radiation do not occur. A continuous record of both this and the pyrheliometer output should be kept during the calibration period to assure there is truly clear sky and steady radiation. Experimenters should stay out of the field of view of the instruments while data are being taken. Even small amounts of radiation reflected from skin or clothing can affect the accuracies.

The equations for transfering calibration from a pyrheliometer (instrument 1, subscript = 1) to a horizontal pyranometer (instrument 2, subscript = 2) are:

$$K_2' = V_1 K_1 \cos (90 - \alpha)/\Delta V_2$$

where: α = the solar elevation (degrees)

V_1 = output of pyrheliometer (mv)

*It is common to use a 10cm diameter disc at a distance of one meter from the pyranometer. The disc is fastened to a long narrow rod on a stand so that it can be put in place and left for a short time.

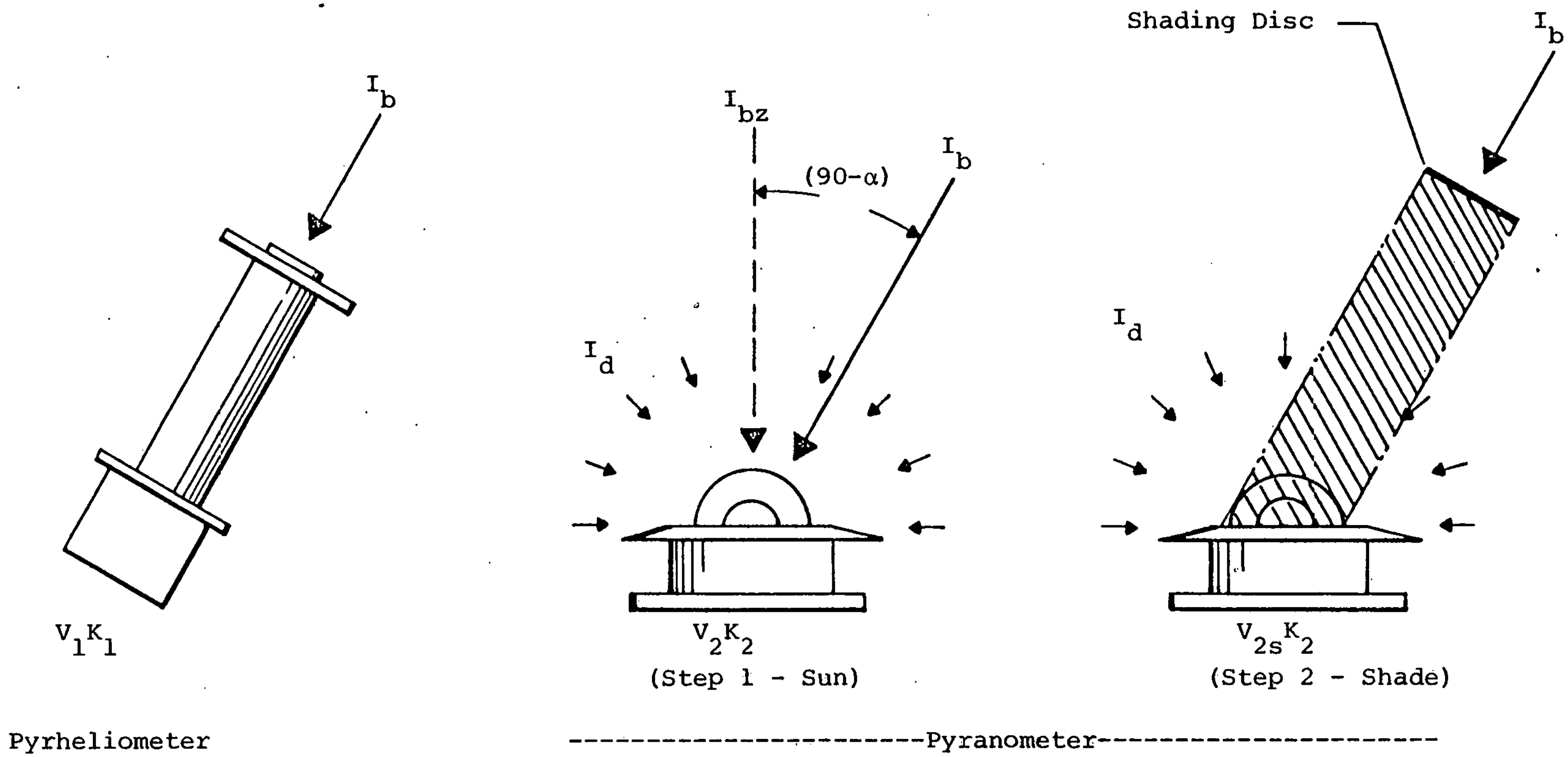

Figure 18. The Sun and Shade Method, with horizontal pyranometer. (Adapted from Reference 3)

$\Delta V_2 = V_2 - V_{2s}$ (mv)

V_2 = output of pyranometer (not shaded) (mv)

V_{2s} = output of pyranometer shaded (mv)

K_1 = calibration constant of pyrheliometer ($KW/m^2/mv$)

K_2 = original calibration constant of pyranometer ($KW/m^2/mv$)

K_2' = new calibration constant of pyranometer ($KW/m^2/mv$)

Note that instruments are often marked with the reciprocal units 10^{-6} $V/W/m^2$. (Just 1/K used here.)

As an example of recalibration let us assume:

$1/K_1 = 6.41 \times 10^{-6} V/w/m^2$, $K_1 = 0.1560$ ($KW/m^2/mv$)

$1/K_2 = 8.93 \times 10^{-6} V/w/m^2$, $K_2 = 0.1120$ ($KW/m^2 mv$)

V_1 = 6.23 mv

V_2 = 7.01 mv

V_{2s} = 0.55 mv $\quad \Delta V_2$ = 6.46 mv

$\cos (90 - \alpha) = 0.731$

Then:

$$K_2' = 6.23 \times 0.1560 \times 0.731/6.46 = 0.1100 \ (KW/m^2/mv)$$

$$1/K_2' = 9.09 \ (10^{-6} V/W/m^2)$$

The change in calibration factors can be calculated from:

$$\% \text{ change} = \frac{K_2' - K_2}{K_2} \times 100 = \frac{0.1100 - 0.1120}{0.1120} \times 100 = 1.8\% \text{ change}$$

This same method could be used to calibrate the pyranometer on a tilt. In this case the angle $(90 - \alpha)$ would be the angle between the direction of maximum sensitivity of the pyranometer (which is the zenith when it is mounted horizontally) and the solar beam radiation.

The calibration of a pyranometer on a tilt can be used to estimate the change of calibration of the pyranometer in the tilted plane from that in a horizontal plane. Note, however, that this method may introduce effects due to interaction with the color of the light reflected from the ground, particularly if the ground cover viewed during calibration was different from that viewed during data collection.

This method for calibrating the pyranometer at a tilt would be most useful for an in-situ calibration, such as on a collector test facility where the pyranometer was not moved between calibration and use.

The same basic procedure is used when calibrating a pyranometer where the pyranometer and the pyrheliometer are both mounted on a tracking platform $(90 - \alpha) = 1$.

The equation is now:

$$K_2' = V_1 K_1 / \Delta V_2$$

The second pyranometer used to assure a constant flux should also be mounted on the tracking platform.

There are a number of factors which limit the accuracy of the foregoing calibration procedure. These are ignored in the equations given, and it has been assumed that the errors due to these factors will be sufficiently small for most uses. With careful procedure, high quality pyranometers, and a high quality absolute instrument for the pyranometer on a very clear day, one should expect repeatability of measures on the order of 0.2% and an absolute accuracy of the calibration on the order of 2.0%. The factors which limit the accuracy of these calibrations include:

- Differential color response. The absolute pyrheliometer normally has no window glazing, but the pyranometer does. This inherently limits the response of the pyranometer at some wavelengths. The pyrheliometer with no glazing could therefore possibly be affected by the far infrared sky radiation or lack of it at wavelengths as long as 40 μm. Different paints on the absorbing surfaces, or slightly different colors due to aging and exposure of the instruments could cause some different responses.

- True view angle factors. The equations assumed that the edge of the disc for shading the pyranometer, and the edges of the window for the pyrheliometer provide geometrically sharp cutoffs. In reality this is not true. There are effects due to: the width of the detector elements in both the pyranometer and the pyrheliometer, (see Figures 8 and 9), the shape of the sensitivity across the detector elements in both (see Figure 16), effects due to refraction of the dome of the pyranometer, effects due to internal reflection inside the tube of the pyrheliometer, and effects due to the diffraction of light on both instruments.

- Reflections from shading disc. It is possible that secondary reflections from the back of the shading disc, or the amount of diffuse sky radiation blocked by the disc support is sufficient to introduce error.

- Other possible effects such as cosine error, temperature errors, etc., which are discussed elsewhere have also been ignored in these equations.

- Variation of the solar flux. Performing experiments on only the very clearest days and near solar noon minimizes the chance of variation. However, there are often high thin clouds invisible to the eye which can be detected as variations in pyrheliometer, or pyranometer output. Alertness to any possible variation in solar flux detected by instruments is important.

2) <u>The Collimation Tube Method</u>

This method is used much less often than the foregoing because it requires a special device to obtain appropriate collimation.

One early pyranometer was constructed with a means for attaching a collimation tube designed to be used with the pyranometer. This instrument is seldom used today because of its limited availability and age.

An example of one type of collimation device is shown in Figure 19. This device can be used to calibrate the pyranometer in either a horizontal position or normal to I_b. A pyrheliometer, not shown in Figure 19, is still required as in the sun and shade method.

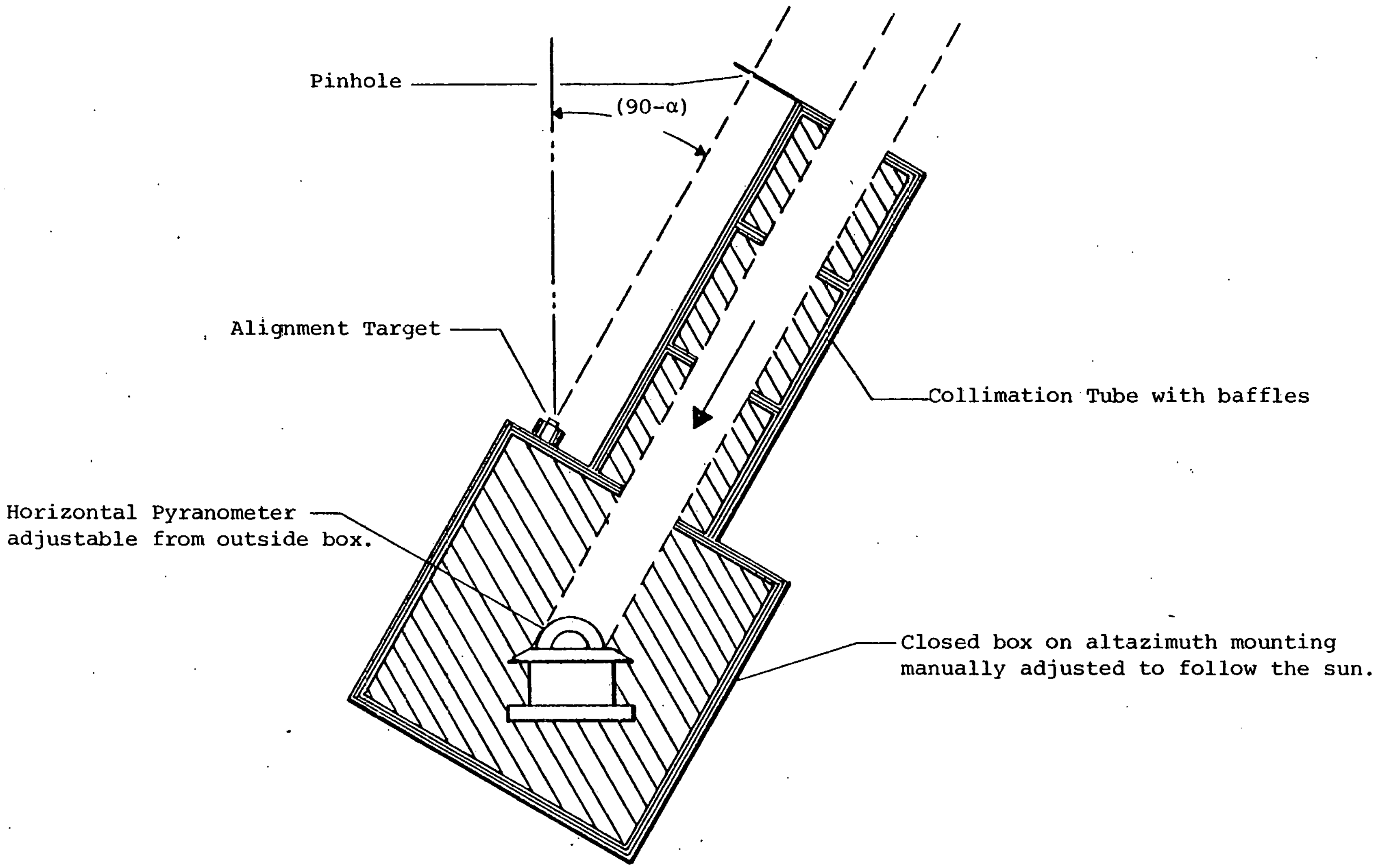

Figure 19. One device which can be used for calibrating with the collimation tube method.
(adapted from reference 3)

The equations for calibration in the horizontal position are:

$$K_2' = V_1 K_1 \cos(90 - \alpha)/V_2$$

and in the normal position:

$$K_2' = V_1 K_1/V_2.$$

Insufficient experience with this method is available to be able to give specific accuracies which can be expected. It is likely that this method would provide calibrations with the same accuracies as the sun and shade method.

Factors which limit the accuracy of this method include:

- All factors discussed for the sun and shade method except for, reflections from the shading disc,

- Reflections from the collimating tube and secondary internal reflections inside the box. This is probably the most difficult to control. The inside of tubes and boxes are always painted a flat black. Even so reflections can be a problem.

d) Determination of Temperature Effects

The most commonly used procedure is to place the instrument inside a temperature controlled box. The instrument is illuminated through a window in the side of the box. The temperature is then cycled slowly through the temperature desired. The rate of change of temperature should be slow enough to eliminate errors due to instrument dynamic response. The atmosphere inside the box must be purged of all water vapor to eliminate condensation and frost. The illumination level inside the box is often monitored to assure constancy.

One experimenter described an experimental setup where the lamp is placed inside the box. This may be expected to place considerable additional load on the cooling mechanism.

e) Determination of Dynamic Response

This test was not regularly performed by any group.

The following procedure is suggested:

1) Allow the instrument to stabilize outdoors on a clear day for at least one hour.

2) Cover just the dome with a completely opaque well insulated cover.

Record continuously the instrument output until it has stabilized again, at least 10 minutes. Repeat steps 1 and 2 until the characteristic has been clearly delineated.

3) Allow the instrument to stabilize outdoors for at least one hour with the cover in place.

4) Remove the cover and allow the reading to stabilize. Record the solar flux continuously with a 2nd pyranometer to assure a baseline for the measurement.

Repeat steps 3 and 4 until the characteristic has been clearly delineated.

This method provides two characteristic functions one for a positive step in illumination and the other for a negative.

f) Measurement of Cosine Response

The best method for measurement of this parameter requires the construction of a special test bed which will hold the pyranometer in a horizontal position, and has a light source which can be positioned at any point on the sky dome with respect to the pyranometer. The experiment should be done in a large darkened room in such a way as to minimize any stray light striking the pyranometer.

Other methods include mounting the pyranometer on the rotatable head of an optical bench and measuring the response variation as the head is rotated. The light source is placed in a horizontal plane at some distance from the pyranometers.

The light source used should have a relatively small apparent angle. Some experimenters have been concerned that the light source be highly collimated.

One possible source would be a powerful laser.

The cosine response test requires adequate energy levels.

Another method sometimes used for a quick check is to perform a procedure similar to the sun and shade calibration throughout the day and to look at the variation of K_2' as a function of α. This method assumes, however, a complete azmuthal symmetry in response.

A complete hemispherical mapping of the cosine response of a series of pyranometers has never been done.

g) <u>The Effects of Tilt on Calibration</u>

This measurement is made by constructing a special test bed which tilts the pyranometer while maintaining a constant illumination. This normally consists of a tube mounted on a bearing with a pyranometer at one end and a light source at the other. The tube must be well ventilated by an exhaust blower to maintain a constant temperature within the tube.

One of these test beds was built with mountings for two pyranometers, one at each end of the tube, and the light source at the center. This allows two instruments to be tested simultaneously, or for one to be compared against another (see Figure 20).

When performing an experiment of this type one must be careful to eliminate the changing effects of gravity on the light source.

h) <u>Determination of the Direction of Maximum Response and Checking Instrument Level</u>

A simple test bed is made for this measurement. The test bed consists of a level rotatable platform with a small close focusing telescope mounted above it and a light source to one side at approximately 60° elevation. Sometimes the light source can be placed at different elevations.

First the platform is checked for level while it is rotated. Then the pyranometer is placed on the turntable and centered using the telescope and leveled using the bubble level on the pyranometer. The centering is rechecked. The light is then turned on and the instrument is rotated. If there is any variation in the output while the instrument is rotated the instrument is releveled (ignoring the pyra-

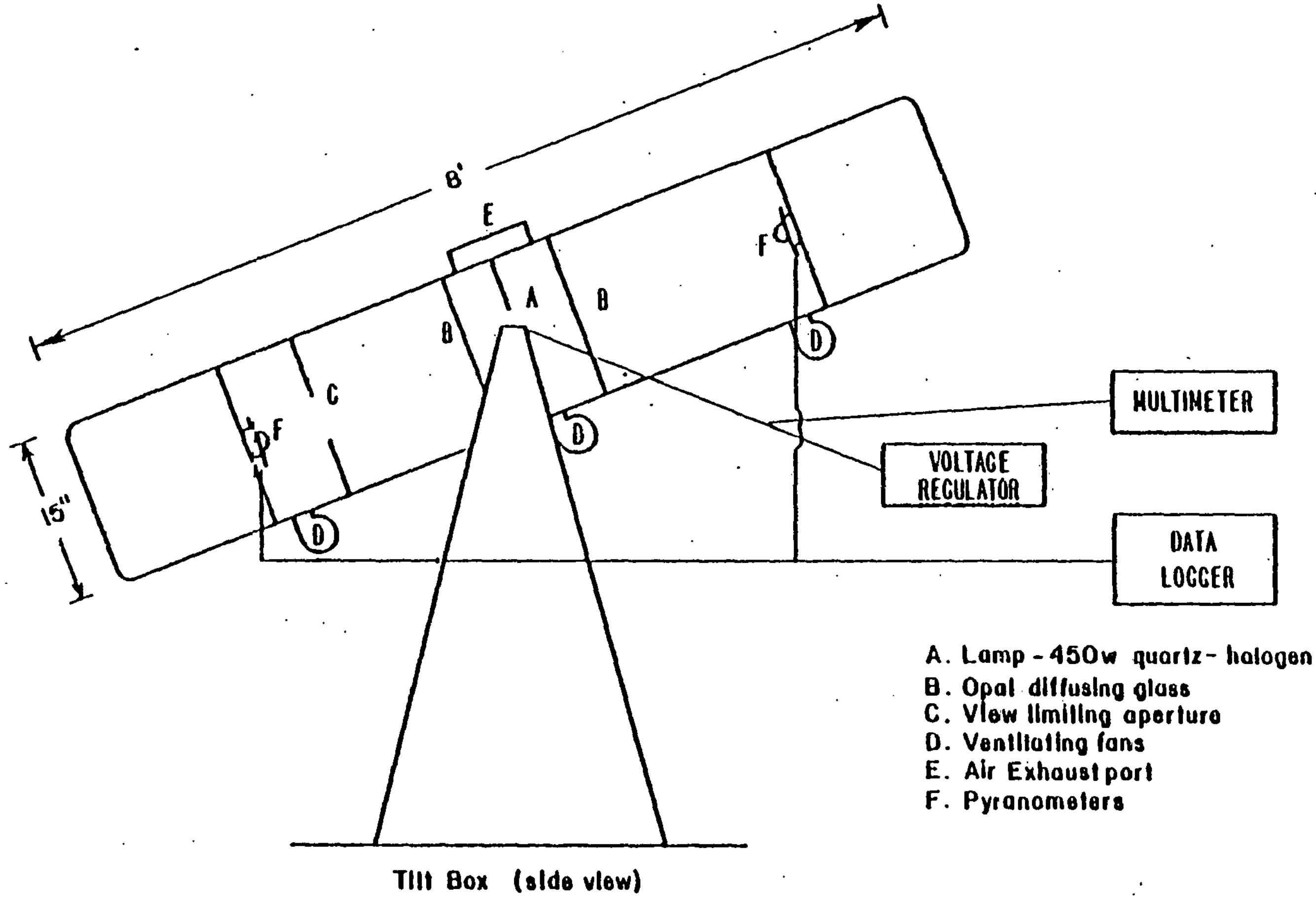

Figure 20. Tilt box for testing effects of tilting pyranometers. (Courtesy of NOAA SRF, Boulder.)

nometer level) until there is no variation of output with rotation. The screws holding the bubble level to the instrument base can be loosened and a shim of the correct thickness placed under the instruments' bubble level to cause proper reading.

i) Determination of Uniformity of Spectral Response

This experiment is seldom done.

The simplest method is to take two instruments which have been carefully checked for calibration and to place them in a simple test bed which allows interposing a variety filters between the light source and the instrument. If both instruments have the same spectral response, the effects of each filter should be the same on both instruments.

j) Linearity

The best measurement of this is made in sunlight with a special rotating shutter. The shutter is constructed so that it forms a disc, a fraction of which is transparent, and another fraction of which is opaque. The relative fractions of opaque and transparent portions of the disc are adjustable. The shutter is placed so that the direct beam energy passing through a transparent section falls onto the pyranometer to be tested. When the shutter is rotated the direct beam is alternately turned on, and off for times which correspond to the relative fractions of the disc transparent and opaque. The rotational speed of the shutter must be fast enough so that variations do not appear in the output of the pyranometer, thus all integrating is done thermally inside the instrument. To get the maximum intensity for this test the pyranometer should be tilted so that it is normal to the beam.

This method of testing would not work for photovoltaic pyranometers.

Another method uses an optical bench where the pyranometer is moved closer to or farther from the light source. This method is not as satisfactory because the geometry of the light source and of the instrument must be considered and it is more difficult to obtain intensities as high as outdoor clear day conditions.

Note that linearity measurements cannot be made with an incandescent lamp and dimmer because such devices change the color of the light as well as the intensity.

k) The Effects of Electrical Impedance

No recorded experiments of this type have been identified.

A simple experiment was performed by the author. An Eppley PSP reading 5.01 mv at the output was loaded by placing a 100,000 ohm resistor across the leads, in parallel with the voltmeter. The voltage dropped to 4.97 mv. This is a change of 0.8%. One hundred thousand ohms is normally considered an extremely small load. A measurement of the D.C. resistance of the instrument showed 650 ohms.

The conclusion here is that in all cases the electrical load must be known, and the instrument should be calibrated with the same electrical loading as is used for collecting data. It is not at all uncommon to find voltmeters or data collection systems with input impedances of 100,000 ohms or less.

Temperature compensation in some instruments include series and or parallel thermistor networks. Thus changing the electrical loading could affect the temperature compensation characteristics of the instrument as well as the calibration factors.

Pyranometer: Determination of Interaction Between Factors

It is customary to assume that there are no interacting factors, and thus only measurements of single characteristics are needed. In each of the foregoing procedures that assumption was made. Few if any experiments have been performed to identify interactions, however, it is not at all obvious that there are no interactions.

When measuring any single characteristic one must be very careful to assure that all other possible parameters are held constant.

The best way to measure interactions is to design an experiment which varies two or more of the parameters in the desired fashion.

Another way is to develop a mathematical model of the instrument and to use that model to investigate the interactions.

The result of these measurements would likely be that the calibration constant K will be treated as a function instead of a constant. With this far more accurate measurements should be possible.

Pyranometer: Calibration With Shadow Bands

There are a variety of shadow bands available.

Correction factors or correction functions should be applied to compensate for: the loss of diffuse skylight blocked by the band; the addition of diffuse due to secondary reflections from the inside of the band; and the effects due to circumsolar radiation. All of these factors vary with time of day, time of year, length of time since last adjustment of the band, the current weather and ground reflectivity. Different shapes and widths of shadow bands will also cause different effects.

No specific procedures for calibrating pyranometers were identified.* One set of calibration factors is given in Appendix C.

*Dr. Inge Dirmhirn of Utah State University at Logan, Utah is currently working on a description of these methods. It is expected that this will be published sometime in the near future.

CALIBRATION OF PYRHELIOMETERS

A pyrheliometer is intended to measure only the direct beam solar radiation falling on a surface normal to the direction of the beam.

Pyrheliometer: The Idealized Instrument

The idealized pyrheliometer is defined as having the following characteristics:

Spectral response and linearity only:

$V = KI_x$ for $0.2\ \mu m \leq x \leq 3.0\ \mu m$,

$V = 0$ for $x < 0.2\ \mu m$ or $x > 3.0\ \mu m$.

The geometric response is defined in terms of the limiting aperture, detector size (both circular), and the instrument length. See Figure 8. It is assumed that the sensitivity across the surface of the detector is uniform. The actual sensitivity along a line passing through the optical axis of the instrument looks like Figure 21, where V is the output in volts, K is the calibration constant, and I_x is the radiation intensity at wavelength x.

The above holds for all temperatures 0°K to ∞, for any environmental condition, wind, rain, etc., and for any electrical load applied to the output terminals of the instrument, and for any angle of tilt.

The output of the instrument illustrated in Figure 21 is a complex function. It represents the area inside both of two circles as one circle is moved with respect to the other. When their centers are separated by a distance equivalent to or less than Z_p, one is completely inside the other. When that distance is greater than Z, there is no overlap. These circles are the images of the field stop and aperture stop illustrated in Figure 8, as seen from a point outside the pyrheliometer.

When the sun is allowed to drift across the front of a pyrheliometer on a clear day the output should look very close to that in Figure 21.

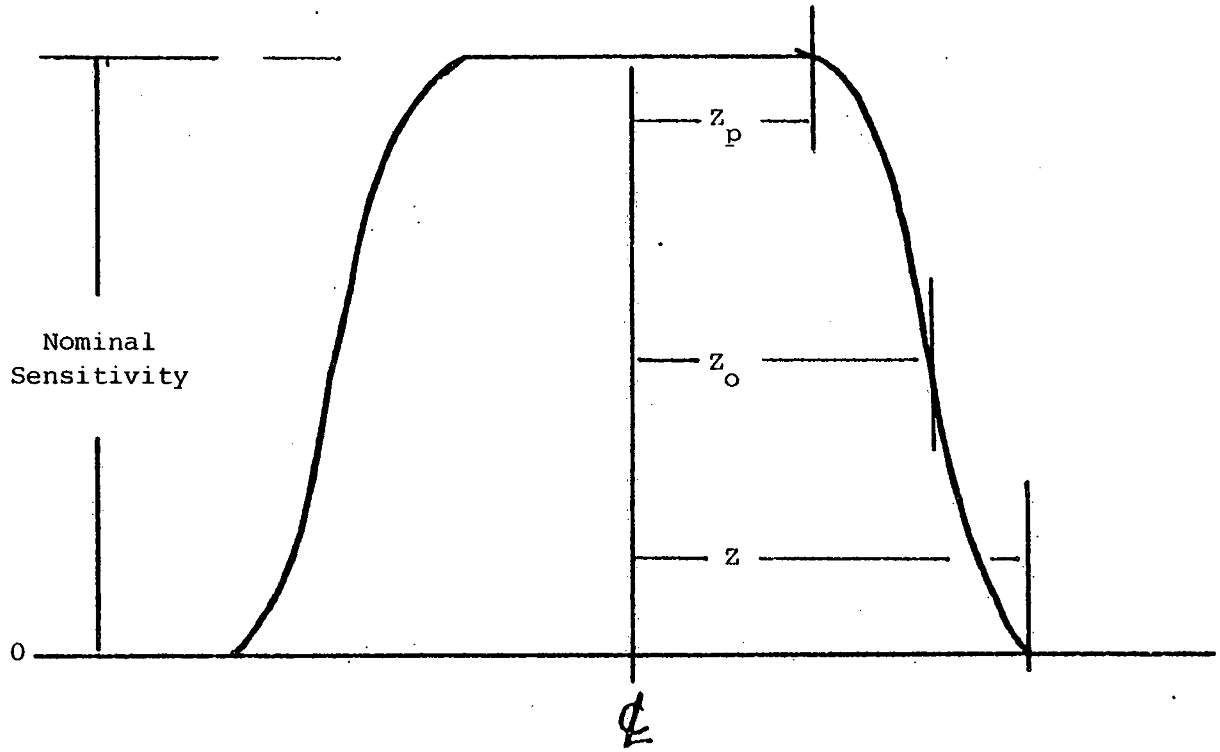

Figure 21. Geometric Response of the Idealized Pyrheliometer.

Differences should be due to the fact that the sun is not truly a point source, but has an angular diameter of about 0.52°, and that circumsolar radiation near the solar disc (see Figure 17) will cause some additional modification of this shape.* The purpose of calibration is to identify the true functional relationships between K, the shape of the curve represented in Figure 21 and a variety of other variables, including I_x, temperature, wind tilt angle, load, etc.

Pyrheliometer: The Factors Normally Evaluated

The following factors are commonly considered when calibrating pyrheliometers:

a) The calibration constant K is determined for some nominal temperature, usually 25°C.

b) The range of variation of K with a given range of temperature.

c) The dynamic response of the instrument (usually specified as a time constant by measuring the response to a step function in illumination and assuming an exponential shape to the functional change).

Pyrheliometer: The Factors Seldom Evaluated

The following factors are seldom evaluated for a variety of reasons:

a) The true shape of the geometric response function, represented in Figure 21.

b) The change of K with angle of tilt.

c) The spectral response of the instrument.

d) The linearity of the instrument.

e) The effects of wind and/or rain on the instrument.

f) The effects of electrical impedance or load applied to the

*Note that this discussion refers to the idealized instrument. Actual instruments could have different responses due to the variation in sensitivity across the detector surface and other things.

output of the instrument.

g) The sensitivity of the instrument in conjunction with its associated load to electromagnetic radiation.

h) Effects due to the effective sky temperature. This could be quite important when intercomparing an instrument such as a NIP which has a glazed window, with an absolute instrument which has none.

i) The effects of reflected radiation or radiant energy from other sources striking the body of the instrument.

j) Determination of the optical axis with respect to the alignment guide.

Pyrheliometer: Procedures for Calibration

The procedures given in this section include both commonly used procedures and some which have never been tried. The user of these procedures must decide for himself which are appropriate for his instrument and the measures he wishes to make with that instrument.

a) Determination of the Calibration Constant

This procedure involves the transfer of calibration from one pyrheliometer type of instrument to another similar type of instrument. This intercomparison is always done in sunlight on a very clear day. One of these instruments is the standard or reference instrument from which the calibration is being transferred. Both instruments are mounted on tracking platforms and properly aligned with the sun. The reference instrument may be an absolute instrument.

Both instruments should be allowed to stabilize for at least one hour. The alignment is then rechecked and data taken.

If the two instruments have different fields of view an estimate of the effect of the circumsolar radiation should be made, if data on the intensity of that radiation is available during the test.

The substitution method is sometimes used in the laboratory. In this method an incandescent light source where the far infrared has been filtered or the temperature of the source otherwise controlled to eliminate excessive infrared, is used to illuminate one instrument.

The output is recorded. Another instrument is then substituted and its output recorded, and so on. The light source must be stable. Only instruments of the same spectral response, i.e., same model and same coatings may be used in this method. This probably has a lower precision than the foregoing method.

b) Determination of Temperature Effects

The most commonly used procedure is to place the instrument inside a temperature controlled box. The instrument is illuminated through a window in the side of the box. The temperature is then cycled slowly through the temperatures desired. The rate of change of temperature should be slow enough to eliminate errors due to instrument dynamic response. The atmosphere inside the box must be purged of all water vapor to eliminate condensation and frost. The illumination level inside the box is often monitored to assure constancy.

c) Determination of Dynamic Response

This test was not regularly performed by any group. The following procedure is suggested:

1) Allow the instrument to stabilize outdoors on a clear day for at least one hour.

2) Cover just the opening with a completely opaque well insulated over. Record continuously the instrument output until it has stabilized again, at least 10 minutes. Repeat steps 1 and 2 until the characteristic has been clearly delineated.

3) Allow the instrument to stabilize outdoors for at least one hour with the cover in place.

4) Remove the cover and allow the reading to stabilize. Record the solar flux continuously with a second pyrheliometer to assure a baseline for the measurement. Repeat steps 3 and 4 until the characteristic has been clearly delineated.

This method provides two characteristic functions, one for a positive step in illumination and the other for a negative.

A knowledge of the dynamic response is particularly important if the pyrheliometer is to be used with an automatically rotated filter wheel. Just assuming an exponential decay is likely to give erroneous results.

d) The Effects of Tilt on Calibration Constant

No group has described a test like this. However, this should be a very important test to perform.

This instrument can be placed in the same test apparatus described for the tilt test on a pyranometer. The test should be essentially the same.

e) Determination of Geometric Response

A simple procedure for estimating the shape of the geometric response is to allow the sun to drift across the field of view on a very clear day. This should probably be done on and off the optical axis as indicated by the alignment mechanism. Records of output of the instrument should be kept with respect to the alignment indicated on the alignment mechanism. A second tracking pyrheliometer should be used to maintain a reference. This method should provide an estimate of the shape of this curve and give an idea of the precision of alignment and tracking necessary for proper operation.

A more precise measurement would require the use of a laser and an optical bench.

f) Determination of Uniformity of Spectral Response

This experiment is seldom done. The simplest method is to take two instruments, both carefully checked and aligned, tracking the sun. Filters are interposed in front of both instruments and any differential response to the same filters is an indication of different spectral response. It is probably best to have two sets of identical filters and to take data with each member of the pair over each instrument.

g) Linearity

This measurement is best made with the rotating shutter described in the pyranometer test.

h) The Effects of Electrical Impedance

No recorded experiments of this type have been identified.

Since the detectors used in pyrheliometers are basically the same as the detectors in pyranometers, the same conclusions are true. In all cases the electrical load on the instrument must be known. 100,000 ohms should be considered a significant loading of the instrument.

ABSOLUTE INSTRUMENTS

Historically, the establishment of a standard or reference of irradiance over the entire solar spectrum has been a very difficult and imprecise process. Many instruments were made and many experiments done to establish scales of solar irradiance. The most recent of these was the International Pyrheliometric Scale of 1956 (IPS-56). Differences among scales by as much as 2 percent were common. These scales were embodied in measurements made by individual instruments or groups of instruments. The periodic intercomparison of instruments was necessary to establish the stability of the instruments and hence these scales, and to provide a means for transferring these calibrations to individual laboratories. Regular international intercomparisons were established on a 5-year basis. The most recent was in 1975.

The basic problem with many of these instruments was that the absorptivity of the flat detector surface was about 0.98 and would vary somewhat from instrument to instrument and possibly from time to time depending on the coating. In the early 1970s a new instrument was developed which was called the PACRAD. This instrument used a cavity instead of a flat surface for a detector, which, because of the geometry and optics gave an effective absorptivity of 0.998. This along with a very complete theoretical analysis* of the instrument design has provided an instrument which references radiation measurements to an electrical standard, with an accuracy of better than 0.3 percent. Subsequent intercomparisons of these instruments show a long-term stability of better than 0.5 percent.

There are currently three commercially available instruments built on the principles embodied in the PACRAD. These are:

1) The Hickey-Frieden sold by Eppley Laboratories,
2) The Kendall MK-VI sold by Technical Measurements, Incorporated, and

*J. M. Kendall, Sr. and C. M. Berdhal, "Two Blackbody Radiometers of High Accuracy," Applied Optics, V. 9, No. 5, May 1970, pp. 1082-1091.

3) The Radiometrics Model 10 sold by California Measurements.

All of these are known as absolute instruments.

The Hickey-Frieden design is based very closely on the original PACRAD design.

The Kendall MK-VI incorporates some improvements from the basic PACRAD and appears to be slightly easier to operate.

Both of the above instruments are switched from calibrate to operate manually. The Radiometrics is built around the active cavity principle where the switching from calibrate to operate is done automatically.

Each of these instruments has advantages and disadvantages. Versions of each of these have flown on rocket flights in attempts to obtain more precise measurements of the solar constant from outside the earth's atmosphere.

The Use of Absolute Instruments

There are two major uses of absolute instruments, first as a standard for calibrating other solar radiation instruments, and second as a method for equating radiometric values to electrical standards. The latter use is primarily done by those who design and evaluate those instruments. The absolute instrument is used by most persons as a standard or reference for calibrating pyranometers and pyrheliometers. The procedures for performing those calibrations were given in the preceding sections. In those calibrations these absolute instruments are used as pyrheliometers, as all three are narrow field of view instruments.

Although some of these absolute instruments are advertised as "all weather instruments" they are normally intended to be used as reference instruments and intended to be used outside on clear days. They should be stored indoors in a clean environment when not in use.

Complete instructions for self-calibration and use of these absolute instruments are normally provided with each instrument purchased. However, most of the tests described as calibration tests for pyrheliometers could be performed for these absolute instruments as well.

DATA RECORDING AND DISPLAY

The majority of this report addresses just the sensors, however, an accurate record and display of the sensor output is required for proper calibration. The recording and display system includes interconnecting wires and any other signal conditioning devices between the sensor (instrument) and the display from which the experimenter reads the output. The most important parameters are:

Resolution

The resolution of the readout system must be better than the accuracy requirements of the final calibration. A good rule-of-thumb is to obtain a system which gives one more digit than is required.

Sensitivity

The sensitivity must be sufficient to detect the smallest signals to be measured. Often this is the same as the resolution.

Accuracy

The accuracy or the precision with which the instruments calibration is referenced to some other standard must be sufficiently well known. This is often less than the resolution, but it must be known if one is to know the accuracy of the calibration of the solar instruments. A good rule-of-thumb is to have an instrument whose accuracy is better than 5 times as accurate as is required for the final calibration.

Input Impedance

The impedance or load across the instruments being calibrated should be the same as the instrument will experience during use.

Speed of Response

The speed of response of the recording and display system should be sufficiently fast to show all the variations in the output of the sensor, when one is interested in understanding the variability of the data. However, integrating recording and display systems may be used when integrated or average measures are desired. Normally, when two instruments are compared the recording and display systems for both should have the same speed of response.

When calibrating the thermopile pyranometers and pyrheliometers discussed in this report, a digital voltmeter with a resolution of 10 microvolts and an accuracy of ±0.05 percent will normally be satisfactory for reading instantaneous outputs of these instruments.

Radio Frequency Interference

Radio frequency interference picked up by the interconnecting cables can often cause serious problems during calibrations. The following steps will help avoid these problems:

1) Locate calibration sites away from radio transmitters of any kind, including radar.
2) Always use shielded and properly grounded cables, and make sure all components of the system are properly grounded.
3) Check for any interference on the input lines at the input to the recording and/or display system with a sensitive oscilloscope. The oscilloscope should respond to at least 25 MHz, preferably higher.

Strip Chart Recorders

Strip chart recorders normally do not have sufficient resolution to be used as recording and display devices for most calibration.

PROGRAM AREAS FOR RESEARCH AND IMPROVEMENT

Throughout this project the authors have had the opportunity to examine the calibration at many individual laboratories. A number of conclusions have been drawn from these observations. These are:

Calibration of instruments is important to the solar program, both short- and long-term, because:

1. The limitations of the accuracy of the data we now collect is due primarily to the methods we use in calibrating our instruments.

2. Our knowledge of how those instruments perform would be increased considerably by more thorough (extensive) calibrations (performance analysis).

3. Mathematical models are now approaching, the same accuracy as we have in our ability to measure the solar radiation. Therefore,

   -without improvement in accuracy, our networks may soon be obsolete

   -without better data, the models cannot improve farther

4. Through increased knowledge of the limitations of existing instruments, we will be able to design new, better ones.

Current state of the art:

Field pyranometer (PSP)	→	±2%
Field pyrheliometer (NIP)	→	±2% maybe ±1%
Absolute pyrheliometer (H-F, TMI)	→	±0.5% to ±0.2%
Absolute pyranometer (JPL)	→	unknown

Convertable pyranometer (Abbott) → These instruments are no longer available. Owners of these instruments claim accuracies of 2% to 0.5% (see Reference 7).

Problems/limiting factors and suggested resolution/programs:

Field pyranometers - limiting factors:

1. Lack of knowledge of potential pitfalls and errors by a large number of users and calibrators.

2. Unknown contribution to total errors of various component errors, e.g., spectral, drift, cosine, linearity, etc.

3. Inability to transfer calibration from pyrheliometers to pyranometers with necessary accuracy.

4. Greater accuracy will require significantly more effort, for example:

   -individual mappings of the cosine response of each instrument and changes with time

   -analytical examination of each instrument for changes in spectral reflectivity and transmissivity

   -developing calibration factors which are a function of weather/sky brightness/sky color/variation of brightness across the sky/or solar position

   -establishing a calibration experiment or facility at a high elevation in a dry southern location

   -lack of knowledge of the effect of air flow over domes or wind on instrument performance

Field pyranometers - suggested programs:

-A simple short technical brochure should be prepared on the use, maintenance and calibration of solar radiation measuring instruments which could be included at nominal cost with each new instrument sold.

-A program for careful intercomparison of instruments calibrated by each of the three methods (sunlight, std. lamp and blackbody) should be established.

-A method should be developed for the precise transfer of calibration from pyrheliometers to pyranometers. The accuracy of this transfer should approach the accuracy of the absolute calibrations. Possibly revive the Abbott convertable.

-An automated test bed which will map the cosine response of pyranometers should be constructed to minimize the labor involved in mapping that response.

-The design and evaluation of a field model of the absolute pyranometer should be encouraged.

-We need to establish (so we can predict) the degradation (change) of pyranometer characteristics, e.g., spectral, temperature coefficient, etc.

-A program to solve the problem of a "standard sky" for calibration and calibration transfer. Possible solutions:

- -high (elevation) and dry (climate), cloudless calibration site
- -all-sky brightness and color monitor to establish color-area characteristics of instruments

Field pyrheliometers - limiting factors:

-lack of knowledge of how good data is

-too few instruments recalibrated yet

-lack of knowledge of error magnitudes and causes

-specific instrument problems:

- -instrument must be aligned/checked daily
- -instrument cannot be aligned when cloudy
- -trackers are difficult to align and there is no quantative way to know when it is aligned
- -dessicant not replaceable

Field pyrheliometers - suggested programs:

-recalibrate more (will happen in time)

-establish a calibration which is a function of atmospheric content, air mass, etc.

-push calibration accuracy to the limit by studying calibration and exposure data, and analyzing exposed instruments

- design and market a higher quality easier to use instrument
- better tracker design

Absolute pyrheliometers - limiting factors:

- unknown drift amounts and causes
- too few and irregular intercomparisons

Absolute pyrheliometers - suggested programs:

- More intercomparisons: select only prime locations for intercomparisons, get good resources for intercomparison, e.g., real time data system, circumsolar telescope data coincidentally, etc.
- Encourage U.S. manufacturers to market internationally.
- Get modelers involved in the intercomparison data reduction.

Absolute pyranometers - limiting factor:

- there are not enough instruments

Absolute pyranometers - suggested program:

- get a number of instruments (~20) in the field

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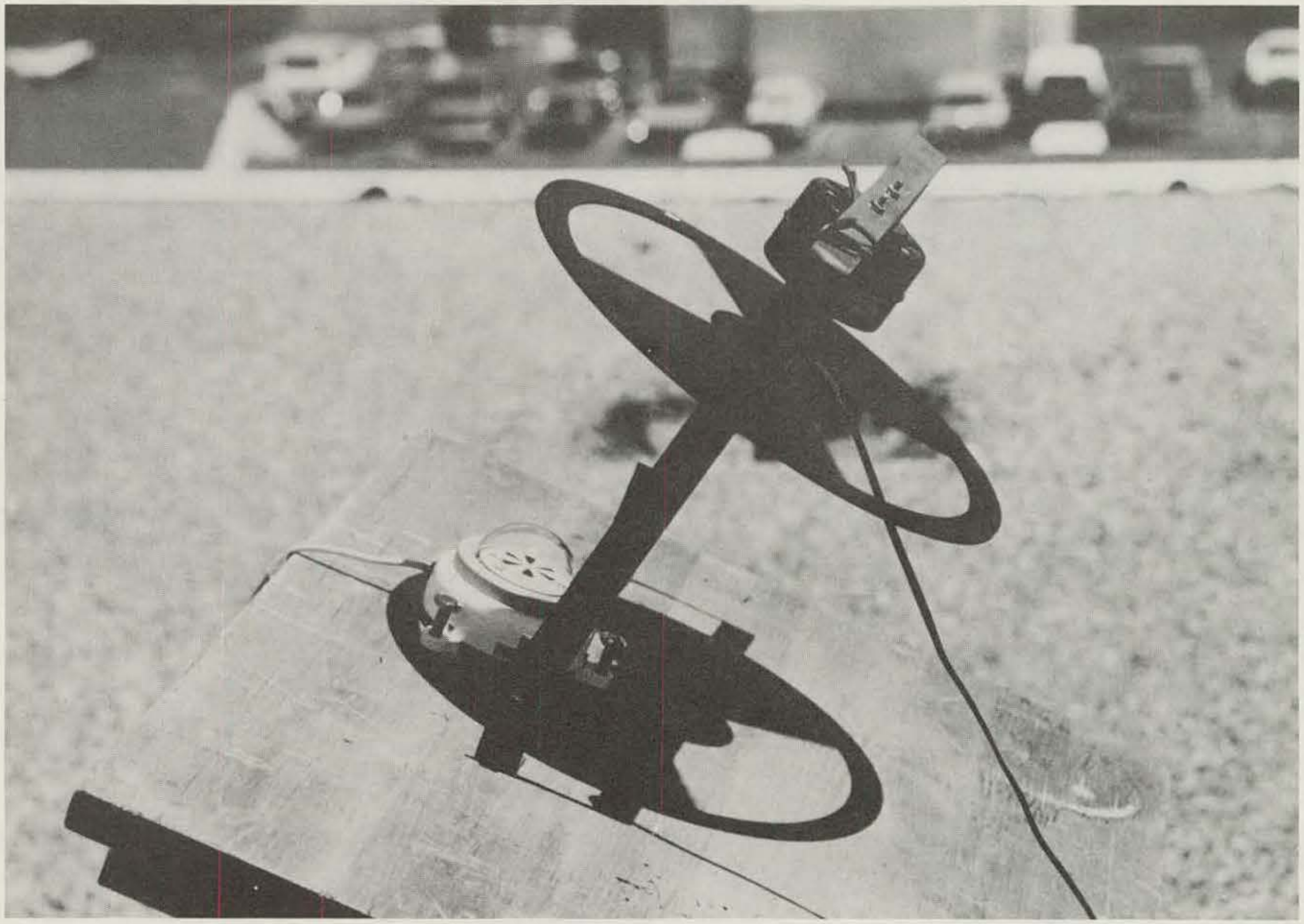
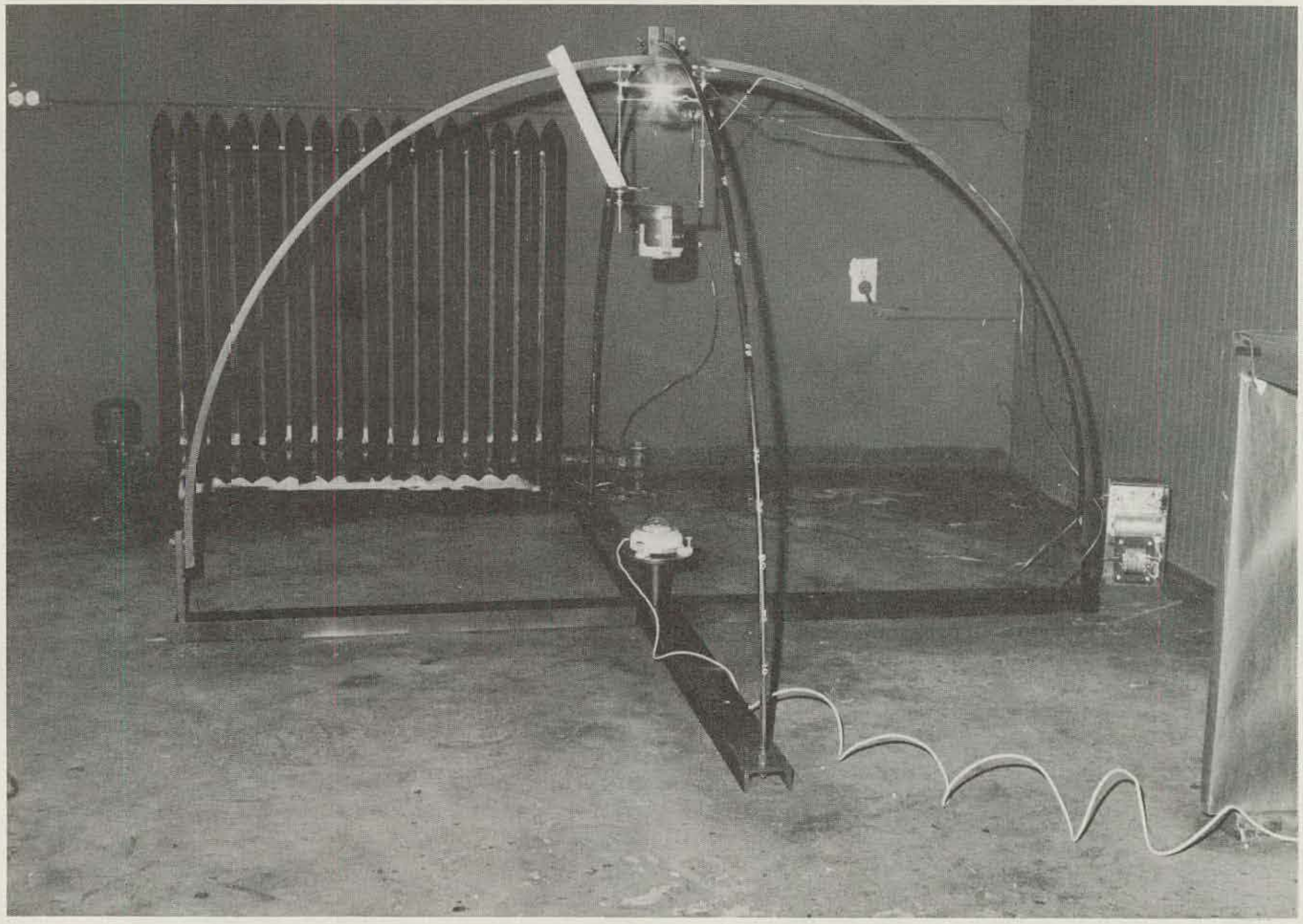
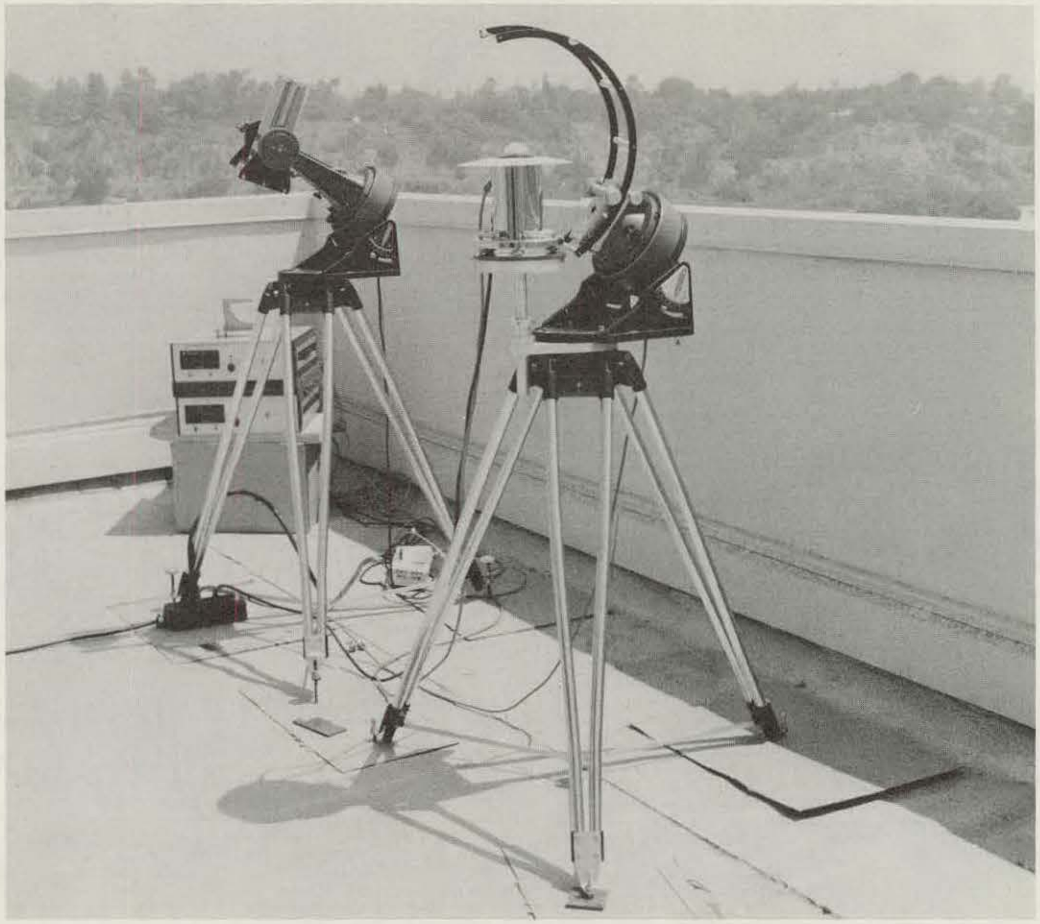
P H O T O   W O R K



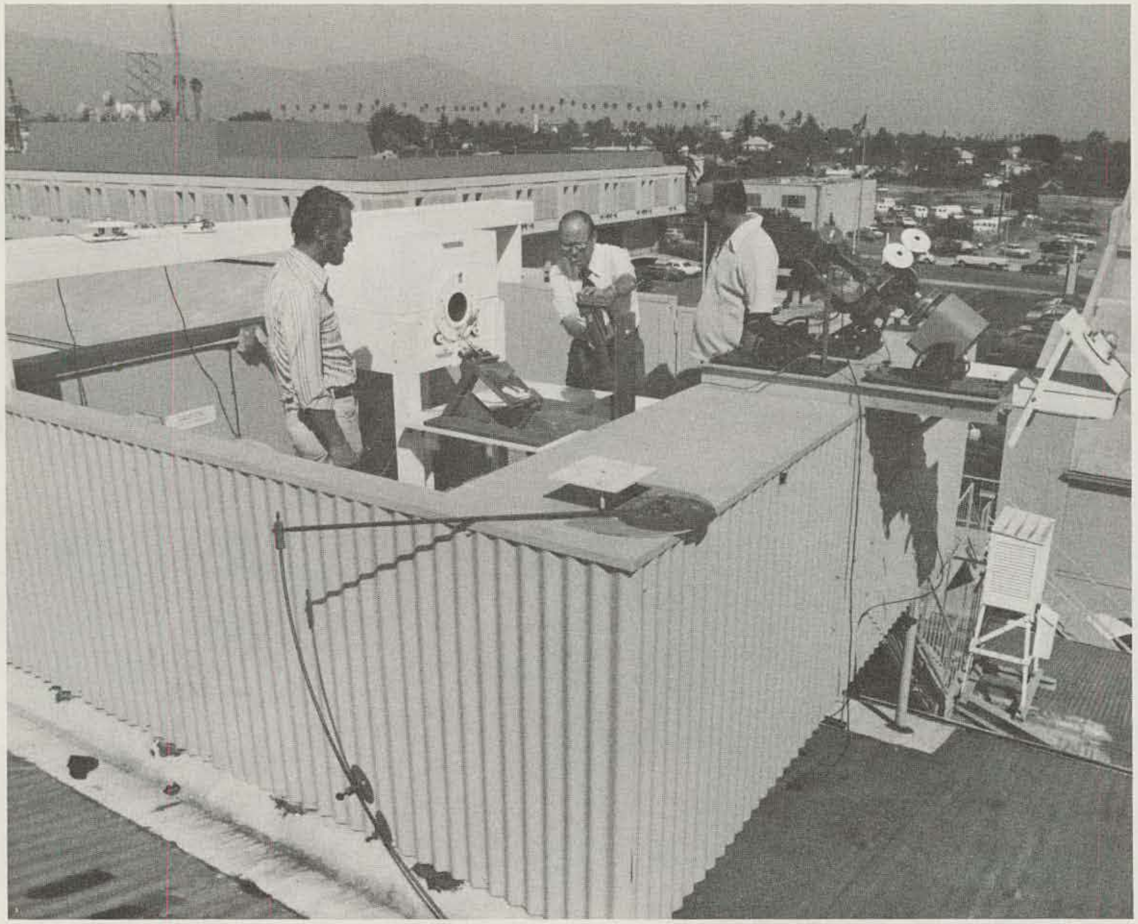
Photograph 1. Test bed for checking linearity of pyranometer. (Courtesy of Dr. Inge Dirmhirn, Utah State University.)



Photograph 2. Test bed for measuring the cosine response of a pyranometer. (Courtesy of Dr. Inge Dirmhirn, Utah State University.)



Photograph 3. TMI Mark IV absolute pyrheliometer and pyranometer with tracking arm to hold disc for sun and shade calibrations. The pyranometer in the foreground is a new experimental absolute instrument embodying the principles of the PACRAD cavity radiometer. (Courtesy Jet Propulsion Laboratory, Pasadena, California.)



Photograph 4. Typical solar instrument calibration facility. An absolute pyrheliometer and two Eppley NIPs are mounted on trackers; shading disc in foreground has been moved out of the way. Operator is aligning an experimental chamber for performing cosine calibrations using reflected solar beam. (Courtesy Mr. Dorr Kimball, Southern California Edison, Rosemead, California.)

APPENDIX A

World Meterological Organization Guide to Meterological Instrument and Observing Practices, Second Edition

Chapter 9 - Measurement of Radiation and Sunshine
Published August 1965

Note: This Chapter of the WMO Guide is out of print and currently unavailable. For that reason it is reprinted here. Hopefully, an updated version will be available soon.

WORLD METEOROLOGICAL ORGANIZATION

GUIDE
TO
METEOROLOGICAL INSTRUMENT AND OBSERVING PRACTICES

Second Edition

WMO - No. 8. TP. 3

SUPPLEMENT No. 5 AUGUST 1965

Replace the present Chapter 9 by the new text, pages IX.1 to IX.55

Table of contents — please read :

CHAPTER 9 — MEASUREMENT OF RADIATION AND SUNSHINE

9.1 General

9.1.1 *Terminology and units*

The terminology used in this chapter is based on the *Terminology of Radiation Quantities and Measuring Instruments* adopted by the WMO Commission for Instruments and Methods of Observation in close collaboration with the Radiation Commission of the International Association for Meteorology and Atmospheric Physics. The full text of the terminology is reproduced in Annex 9.A.

The preferred units for radiative flux per unit area are milliwatts per square centimetre (mW cm^{-2}) and for radiation amount per unit area either joules per square centimetre (J cm^{-2}) or milliwatt-hours per square centimetre (mW hr cm^{-2}). In some countries a calorie per square centimetre is designated a langley and the corresponding unit of flux is langley per minute (ly min^{-1}). The conversion factors for the different units are given in the appendix to Annex 9.A.

The difference between various standard calories can be ignored in meteorological practice.

9.1.2 *General requirements*

The different radiation fluxes to and from the earth's surface are amongst the most important terms in the heat economy of the earth as a whole and of any individual place at the earth's surface or in the atmosphere. Radiation measurements are of great value for the following purposes :

(*a*) The study of the transformation of energy within the system earth-atmosphere and its variation in time and space.

(*b*) The analysis of the atmosphere with regard to its turbidity and constituents such as dust and water vapour.

(*c*) The study of the distribution and the variations of incoming, outgoing and net radiation.

(*d*) The satisfaction of the needs of biological, medical, agricultural, architectural and industrial activities with respect to radiation.

Such a programme infers widely distributed regular series of records of solar and terrestrial surface radiation components, and the derivation of representative measures of the net radiation. Apart from promoting the publication of serial values for individual observing stations, an essential object must be the production of comprehensive radiation climatologies, whereby the daily and seasonal variations of the various radiation constituents of the general thermal budget may be more precisely evaluated and their relationships with other meteorological elements better understood.

9.2 Classification of radiation fluxes

9.2.1 *Solar radiation*

Measurements of the flux of solar radiation penetrating to the lower layers of the atmosphere can be sub-divided conveniently into seven main classes.

(*a*) Direct solar radiation measured at normal incidence.

(*b*) Global solar radiation received on a horizontal surface. This includes both radiation received direct from the solid angle of the sun's disc and also radiation that has been scattered or diffusely reflected in traversing the atmosphere.

(*c*) Sky radiation. This is the second component mentioned above of the global solar radiation.

(*d*) Reflected solar radiation (Annex 9.A, III.2.2.1).

(*e*) Direct solar, global solar or sky radiation in restricted portions of the spectrum. Included in this category as a special case is the measurement of daylight illumination (Annex 9.A, III.3.1, 2.1.1 and 2.1.1.2).

(*f*) Measurements are also made of the solar radiation falling on a spherical receiving surface. These attempt to simulate the solar radiation environment of an isolated object.

(*g*) Also occasionally made for special purposes are measurements of the global radiation received on a fixed plane surface other than the horizontal; for example on a vertical surface facing south. These measurements will not be considered in detail in this publication but much of the information given will be relevant.

The ratio of the sky radiation to the global solar radiation fluctuates markedly, being unity when the sky is densely overcast but falling below 0.1 in extremely clear conditions.

Because of absorption by oxygen and ozone at high levels of the atmosphere, the short wave-length limit of solar radiation received at the earth's surface is approximately 290 millimicrons (mμ) (the lowest wave-length at which any detectable radiation has been received is 286 mμ). The long-wave radiation lower limit (defined so as to exclude less than one per cent of the total solar radiation) is approximately 4 μ.

9.2.2 *Terrestrial radiation fluxes*

By terrestrial radiation is to be understood the thermal radiation of the earth and the atmosphere. Up to heights of 80 km or more the temperature generally lies within the range —80° to +40° Celsius so that the spectral limits of this radiation (chosen so as to exclude less than 1 per cent of the black body radiation at either end) are 4 μ and 100 μ. None of the three most common of the permanent atmospheric gases (nitrogen, oxygen and argon) absorbs radiation in these wave-lengths but water vapour, carbon dioxide and ozone all have important absorption regions. Ground and clouds radiate in this wave-length region approximately as black bodies.

The terrestrial radiation is a diffuse flux and is usually measured as the flux through a horizontal surface. It is important to distinguish between the flux in one direction only and the net flux of terrestrial radiation, the difference of the downward and upward fluxes.

9.2.3 *Total radiation fluxes*

By total radiation is to be understood the sum of the solar and the terrestrial radiation. The flux of both radiation components passing through a horizontal plane is called net radiation.

9.2.4 *Classification of radiation instruments*

9.2.4.1 *Pyrheliometer*

A pyrheliometer is an instrument for measuring the intensity of direct solar radiation at normal incidence; it can either be a primary standard instrument or a secondary instrument scaled by reference to a primary instrument.

9.2.4.2 *Pyranometer*

A pyranometer is an instrument for the measurement of the solar radiation received from the whole hemisphere. It is suitable for the measurement of the global or sky radiation (Annex 9.A, IV.2.2).

9.2.4.3 *Pyrgeometer*

A pyrgeometer is an instrument for the measurement of net atmospheric radiation on a horizontal upward facing black surface at the ambient air temperature (Annex 9.A, IV.2.3).

9.2.4.4 *Pyrradiometer*

A pyrradiometer is an instrument for the measurement of both solar and terrestrial radiation (total radiation) (Annex 9.A, IV.2.1).

9.2.4.5 *Net pyrradiometer*

A net pyrradiometer is an instrument for the measurement of the net flux of downward and upward total (solar, terrestrial surface and atmospheric) radiations through a horizontal surface (Annex 9.A, IV.2.4).

9.2.5 *Spectral response of radiometers*

Except for illumination-measuring instruments, it is usually desirable that radiometers should respond equally to equal amounts of energy whatever the wave-length of the radiation within the wave-length range they are intended to cover.

Various black surface coatings have been used to attain this end. Foitzik and Hinzpeter (1958) discuss some of these. Various factors affect the choice of black material. If the sensitive surface is to be exposed to the weather a paint coating will be necessary and many black paints are quite unsuitable. Parsons' Optical Matt Black Lacquer has been found to have a high and uniform absorptivity over a wide range of wave-lengths.

9.2.6 *Standard scale of radiation*

Radiation is measured in energy units and these units, as such, are of course strictly defined. Routine radiation measuring instruments can however only be calibrated by comparison with a "standard" radiation instrument whose sensitivity is calculable from more fundamental measurements such as length, electrical current and resistance, and temperature. Because however of small systematic errors and other differences, measurements based on the two main radiation instruments, the Ångström and the Smithsonian standard pyrheliometers (see paras. 9.3.1 and 9.3.2) do not exactly agree and in 1956 an International Radiation Conference at Davos recommended the adoption of a new scale, the "International Pyrheliometric Scale 1956". In effect it recommends suitable corrections to both the Ångström and Smithsonian standards to bring them into line with each other and, it is believed, to make the units of the radiation measurements more nearly equal to the rigidly defined physical units.

The IPS 1956 scale was brought into effect from 1 January 1957. To express radiation measurements in this scale, measurements made according to the original uncorrected Ångström scale should be increased by 1.5 per cent and measurements made according to the Smithsonian scale of 1913 should be decreased by 2.0 per cent.

A full discussion of the reasons for the changes and the evidence for them can be found on pages 378–379 of the IGY Instruction Manual (CSAGI, 1958).

9.2.7 *Standard time for radiation measurements*

All radiation measurements should be referred to what is known in some countries as Local Apparent Time (L.A.T.) and in others as True Solar Time (T.S.T.). For conversion from clock time to sun time reference should be made to any standard Astronomical Almanac taking into account the longitude and equation of time.

9.2.8 *Accuracy of radiation measurements*

Considerable care and attention to detail is required if the desirable standard of accuracy is to be obtained and it is important that the staff engaged on this work should be keen and of a critical disposition.

To estimate the accuracy of radiation measurements made with radiometers the following properties of the complete system (including the measuring, recording or integrating device) will need to be evaluated as appropriate; where necessary, corrections should be applied to the observed results:

(*a*) The sensitivity of the system, i.e. the smallest change in the quantity being measured which can be detected by the system.

(*b*) The stability of the calibration factor, i.e. the maximum permissible change in this factor, per cent per year.

(*c*) The maximum error due to variation in ambient temperature.

(*d*) Errors caused by a departure from the assumed spectral response of the receiver; the maximum error should be assessed in per cent.

(*e*) Non-linearity of the response of the system when this is assumed linear; the maximum error should be assessed.

(*f*) In the case of pyrheliometers, the effect of the circumsolar radiation, which depends on the aperture angle (Annex 9.B).

(*g*) The time constant of the system, i.e. the time necessary to record 1/e of a sudden change in radiation. (For observations made in this way it is necessary to wait up to 4 times this value to obtain a steady reading.)

(*h*) *and* (*i*) The deviation of the directional response of the receiver from that assumed (usually known as the cosine response (*h*) and the azimuth response (*i*)). For pyranometers it is convenient to assess the error in per cent due to this cause when the sun is at an elevation of 10° on a clear day. The effect of auxiliary equipment used with pyrheliometers and disturbing effect of wind on net pyrradiometers must also be considered.

Based on these considerations, Table 9.1 has been produced showing the desirable limits for standard pyrheliometers, first class, second class and third class secondary instruments. Existing radiometers have been classified in the above groups by a working group of the Commission for Instruments and Methods of Observation, as follows:

(i) *Standard pyrheliometer*

Ångström compensation pyrheliometer (Stockholm) (see 9.3.1)
Silver disc pyrheliometer (Smithsonian) (see 9.3.2).

(ii) *1st class pyrheliometer*

Michelson bimetallic pyrheliometer (see 9.3.3)
Linke-Feussner iron-clad pyrheliometer (see 9.3.4)
New Eppley pyrheliometer (1958) (see 9.3.5)
Yanishevsky thermoelectric pyrheliometer (see 9.3.7).

TABLE 9.1

The classification of accuracy of radiometers

	(a) Sensitivity (mW cm-2)	(b) Stability	(c) Tempera-ture	(d) Selectivity	(e) Linearity	(f) Aperture	(g) Time constant (max.)	(h) Cosine response	(i) Azimuth response	*Errors in auxiliary equipment* Gal-vano-meter	mA meter	Chrono-meter
		%	%	%	%			%	%		%	
Standard pyrheliometer	± 0.2	± 0.2	± 0.2	± 1	± 0.5	(1)	25 s	—	—	0.1 unit	0.1	0.1 s
Secondary instruments												
1st class pyrheliometer	± 0.4	± 1	± 1	± 1	± 1	(1)	25 s	—	—	0.1 unit	0.2	0.3 s
2nd class pyrheliometer	± 0.5	± 2	± 2	± 2	± 2	(1)	1 min	—	—	0.1 unit	± 1	—
											Errors in recording apparatus	
1st class pyranometer	± 0.1	± 1	± 1	± 1	± 1	—	25 s	± 3	± 3		0.3	
2nd class pyranometer (2)	± 0.5	± 2	± 2	± 2	± 2	—	1 min	± 5–7	± 5–7		± 1	
3rd class pyranometer	± 1.0	± 5	± 5	± 5	± 3	—	4 min	± 10	± 10		± 3	
											Errors due to wind	
											%	%
1st class net pyrradiometer	± 0.1	± 1	± 1	± 3	± 1	—	½ min	± 5	± 5		± 0.3	± 3
2nd class net pyrradiometer	± 0.3	± 2	± 2	± 5	± 2	—	1 min	± 10	± 10		± 0.5	± 5
3rd class net pyrradiometer	± 0.5	± 5	± 5	± 10	± 3	—	2 min	± 10	± 10		± 1	± 10

Notes: The letters heading the columns refer to the subdivision of section 9.2.8.

(1) See Annex 9.B.

(2) For spherical Bellani, with regard to daily sums only.

(iii) *2nd class pyrheliometer*

Moll-Gorczynski pyrheliometer (see 9.3.6)
Old Eppley pyrheliometer (before 1958) (see 9.3.5).

(iv) *1st class pyranometer*

Selected thermopile pyranometers.

(v) *2nd class pyranometer*

Moll-Gorczynski pyranometer (see 9.5.5.1)
Eppley pyranometer (called 180° pyrheliometer) (see 9.5.5.3)
Volochine thermopile pyranometer (see 9.5.5.4)
Dirmhirn-Sauberer pyranometer (see 9.5.5.5)
Yanishevsky thermoelectric pyranometer (see 9.5.5.6)
Spherical Bellani pyranometer (see 9.7).

(vi) *3rd class pyranometer*

Robitzsch bimetallic pyranometer (see 9.5.5.7).

The secondary instruments at regional or national radiation centres should preferably be of the first class; at principal and other radiation stations they should be either of the first or second class. It is realised, however, that this may not yet be possible for some measurements.

The standard instruments on which the IPS 1956 scale of radiation is based have an absolute accuracy of almost certainly $\pm$ 1 per cent and probably of $\pm$ 0.5 per cent when the recommended adjustment to IPS 1956 has been made. The accuracy of other measurements made by instruments which have been compared with the standard varies with the conditions. A comparison of two similar instruments of the Ångström or silver disc type under very steady conditions can be made to be better than $\pm$ 0.5 per cent but in the calibration of a precision pyranometer by means of a pyrheliometer an accuracy of $\pm$ 1 per cent can only be achieved by very detailed and careful work in good observing conditions.

Nicolet (1948) has stated that in a continuous record of the global radiation of sun and sky an accuracy of $\pm$ 5 per cent in the short term integrated totals represents the result of good and careful work. It is this standard or better accuracy which all radiation measuring stations should try to achieve and this can only be done by conscientious and continuous calibration and inter-comparison of instruments and recording equipment. The accuracy attained by net pyrradiometers is more problematical and is discussed later.

9.2.9 *Measurement of the output of radiometers using thermopiles*

Many radiation instruments incorporate thermopiles as their sensitive elements and the outputs are measured as small electromotive forces. The measuring equipment to be used depends on the range of signal expected, the accuracy and sensitivity required and the resistance of the thermopile. For instantaneous measurements good quality portable potentiometers are often very suitable or, for less precise work, the thermopile can be connected to a pointer type millivoltmeter (microammeter) of suitable range and accuracy. For continuous records automatic self-balancing potentiometers are very reliable. Alternatively precision recording microvoltmeters are suitable, particularly at stations where electrical power is not readily available.

When records have to be made from several sensors, multi-point instruments can be used. Consideration should also be given to the saving in time and labour and, possibly, increased accuracy, that can be obtained by using automatic integration and printing devices. Such equipment can have continuous integrators or may use sampling techniques, and either may be had with analogue-to-digital conversion followed by output on punched paper or magnetic tape. It is possible to incorporate the application of appropriate scaling factors if necessary so that the final printed figures are in the appropriate absolute units.

It is impracticable to give detailed recommendations in this publication since the needs of different services vary widely and also since this is a field in which rapid changes and improvements are taking place at the present time.

The recording circuits must of course be checked regularly ; it is preferable to check at several points over the scale to ensure that the calibration is maintained. The measuring circuit should ideally have a zero temperature coefficient.

9.3 Measurement of direct solar radiation (normal incidence radiation)

Direct solar radiation is measured by means of pyrheliometers, the receiving surfaces of which are arranged to be normal to the line joining the sun to the receiver ; by means of diaphragms only the radiation from the sun and a narrow annulus of sky is measured. The construction of the mount carrying the pyrheliometer must allow rapid and smooth adjustment of the azimuth and elevation to be made. A sighting device is usually included in which a small spot of light falls upon a mark in the centre of the target when the receiving surface is exactly normal to the direct solar beam.

For continuous recording an equatorial mounting is required. Great care must be exercised to ensure that the principal axis is parallel to the axis of the earth's rotation ; the adjustments in both azimuth and elevation should be correct to within $\frac{1}{4}°$. These instruments should be inspected at least once per day and more frequently if weather conditions require it.

The principal exposure requirement for a recording instrument is the same as that for an ordinary sunshine recorder ; that is, freedom from obstructions to the solar beam at all times and seasons of the year. Furthermore the site should be chosen so that the incidence of fog, smoke and airborne pollution is as typical as possible of the surrounding area.

Practical instruments have an aperture slightly larger than required to measure the direct solar radiation, thus causing errors due to radiation from the immediate environment of the solar disc. These errors increase with increasing aperture and can be eliminated only to a certain extent.

The principal instruments in use are described briefly below.

9.3.1 *Ångström compensation pyrheliometer*

In the Ångström compensation pyrheliometer a thin blackened shaded manganin strip is heated electrically until it is at the same temperature as a similar strip which is exposed to solar radiation. Under steady state condition (both strips at identical temperature) the energy used for heating is equal to the absorbed solar energy. Thermocouples on the back of each strip, connected in opposition through a sensitive galvanometer or other null detector, are used to test for the equality of temperature. The energy I of the direct radiation is calculated by means of the formula $I = ki^2$ where i is the heating current in amperes and k a dimensional and instrumental constant. The rectangular apertures in use are $24° \times 6°$ for the short tube instrument and $6° \times 3°$ for the long tube instrument.

Although such an instrument can be made absolute by the calculation of k, in practice most Ångström instruments are calibrated by comparison with one of a few standard instruments.

The auxiliary electrical equipment is important. The d.c. milliammeter should be of accuracy $\pm$ 0.25 per cent or better and individually calibrated so that corrections can be applied. If less precise meters are used it is essential that they be checked each time they are used. It is also preferable that multi-range instruments be used so that the measurements can always be made at more than half of the full scale deflection. The temperature sensing device needs to be of adequate sensitivity ; in general it should be capable of detecting a potential of at least 1 microvolt but for the highest accuracy it should respond to ¼ microvolt. The distance between the milliammeter and the zero galvanometer should be sufficient to avoid mutual interference. Otherwise special precautions in construction will be essential to prevent any parasitic magnetic fields affecting their readings.

9.3.2 *Silver disc pyrheliometer*

The silver disc pyrheliometer, designed at the Smithsonian Institution at Washington, D.C., consists essentially of a blackened silver disc positioned at the lower end of a tube with diaphragms to limit the whole aperture angle to 5.7°. A mercury-in-glass thermometer is used to measure the temperature of the disc. A shutter is used to allow solar radiation to fall on the disc at regular intervals and the corresponding changes in temperature of the disc are measured. A precise routine must be followed and the temperature readings require corrections for air, stem and bulb temperatures. The timing of the operation of the shutter in particular must be very accurate ; a consistent error of one second may, for instance, result in errors of about 1 per cent in the final result.

The instruments must of course be calibrated against a primary standard but their stability has been found to be very good and they are widely used for calibrating pyranometers.

9.3.3 *Michelson bimetallic pyrheliometer*

In the Michelson bimetallic pyrheliometer, the deflexion of a very fine bimetallic strip, when heated by solar radiation, is observed through a low-power microscope. The rectangular aperture of the instrument has angles of approximately 10° and 25°. It is a portable self-contained instrument and is especially suitable for daily "spot" measurement.

The instrument constant is obtained by calibration against a primary standard instrument. The time required for essentially full response is 20–30 seconds.

9.3.4 *Linke-Feussner pyrheliometer*

The Linke-Feussner pyrheliometer uses a Moll thermopile protected by a thick shell of copper. This heavy mass acts as a shield from air currents and helps to maintain uniformity of temperature in the neighbourhood of the receiving surface apart from the conical aperture of about 11° in angle. In the newer instruments the thermopile is made of two equal sections connected in opposition, one of which is shaded from the radiation to be measured and one exposed, but both of which are equally exposed to temperature fluctuations caused by quasi-adiabatic air pressure changes which are particularly troublesome in gusty winds.

In the newer model the time for 99 per cent response to a sudden change is about 10 seconds.

9.3.5 *Eppley (normal incidence) pyrheliometer*

The sensitive element in an Eppley pyrheliometer is a temperature-compensated bismuth-silver thermopile mounted at the base of a brass tube, the limiting diaphragms of which subtend an angle of 5.7°. During manufacture the tube is filled with dry air and is sealed with a crystal quartz window which is removable. A filter wheel (for the three standard meteorological filters) is standard. The response time for over 99 per cent signal is about 20 seconds. The older version of this instrument has a copper-constant and uncompensated thermopile (response time about 6 seconds).

It is a stable instrument and provided proper care is taken can be used as a secondary standard.

9.3.6 *Moll-Gorczynski pyrheliometer*

The Moll-Gorczynski pyrheliometer incorporates a Moll type thermopile. Two main models exist. The first consists of a thermopile in a short tube and is used for spot readings. In the second model, used for recording, a wire frame carries three circular diaphragms so spaced from the thermopile that the angular aperture is about 8°. The thermopile is permanently protected by a glass cover.

9.3.7 *Yanishevsky thermoelectric pyrheliometer*

The Yanishevsky thermoelectric pyrheliometer incorporates a symmetrical star-shaped thermal battery, and has an angular aperture of 10°, which is twice the diameter of the sensor. Battery sensitivity is about 0.1 mV per mW cm^{-2}. The 99 per cent response time is about 25–30 seconds.

9.3.8 *Standardization of pyrheliometers*

The primary standard normally used is either the Ångström pyrheliometer or a silver disc pyrheliometer. Standardization is straightforward provided a day with reasonably steady solar radiation is chosen and a sufficient number of observations are made. Regard must always be paid to the temperature coefficient of each instrument being calibrated, the temperature at which a particular calibration factor is correct always being stated. Comparisons of pyrheliometers should only be carried out when the ratio of the transmission factor to the optical air mass exceeds 0.17. For lower ratios different readings may be observed at varying aperture angles.

Annex 9.C contains some suggested rules to be observed for ensuring the required accuracy in international pyrheliometric comparisons (WMO, 1964).

9.4 The spectral distribution of solar radiation

Measurements are often made of the amount of radiation in broad spectral bands ; the simplest way of doing this is by placing a suitable filter in front of the receiver. Specific filters recommended for use internationally are No. OG1, RG2 and RG8 manufactured by Schott und Gen. (Mainz). Ideally these have the following characteristics :

OG1 opaque up to 525 mμ ; transparent 525 mμ to 2800 mμ
RG2 opaque up to 630 mμ ; transparent 630 mμ to 2800 mμ
RG8 opaque up to 700 mμ ; transparent 700 mμ to 2800 mμ

By the comparison of measurements with these filters and with glass and quartz filters, the amount of solar radiation in various bands can be deduced. A series of such filters has been examined with a spectrophotometer and the parameters of transmission published (Ångström and Drummond, 1961). Table 9.2 summarizes the variation in the position of the centre of lower wave-length cutoff with temperature and thickness, while Table 9.3 shows the variation in transmittance in the main transmission region with glass thickness.

TABLE 9.2

Variation in the position of the centre of lower cutoff (in mμ) with temperature and thickness

t(°C)	1.0 mm OG1	1.0 mm RG2	1.0 mm RG8	2.0 mm OG1	2.0 mm RG2	2.0 mm RG8	3.0 mm OG1	3.0 mm RG2	3.0 mm RG8	4.0 mm OG1	4.0 mm RG2	4.0 mm RG8
−20	522.0	616.5	682.5	527.0	621.0	688.5	530.0	624.0	692.5	532.5	626.5	695.5
−10	523.5	618.0	684.0	528.5	622.5	690.5	531.5	625.5	694.5	534.0	628.0	697.5
0	524.5	619.5	686.0	529.5	624.0	692.0	532.5	627.0	696.0	535.5	629.5	699.0
+10	526.0	621.0	688.0	531.0	625.5	694.0	533.5	628.5	698.0	536.5	631.0	701.0
+20	527.0	622.5	689.5	532.0	627.0	695.5	535.0	630.0	699.5	537.5	632.5	702.5
+30	528.0	623.5	691.0	533.0	628.0	697.0	536.0	631.5	701.0	538.5	634.0	704.0
+40	529.5	625.0	693.0	534.5	629.5	699.0	537.5	632.5	703.0	540.0	635.5	706.0

TABLE 9.3

Variation of transmittance in the main region with glass thickness

Thickness (l)	1.0 mm	2.0 mm	3.0 mm	4.0 mm
Transmittance (T)	0.912	0.909	0.907	0.903

To obtain the amount of solar radiation in all wave-lengths longer than the lower cutoff it is of course necessary to multiply the amount measured behind the filter by a factor given by the inverse of the values in Table 9.3. Each individual filter should however be examined since the position of the lower wave-length cutoff may vary from the ideal value by up to ± 10 mμ and the filter factor ($^1/_T$) may vary by ± 0.005 in general. It is usually desirable to correct the measurements of solar radiation made with an individual filter to those which would have been obtained using an ideal filter of the same type. This can be done by applying the additive corrections given in Table 9.4.

TABLE 9.4

Values in μWcm⁻² of the additive correction corresponding to a wave-length shift of + 10 mμ in the lower wave-length cutoff for specified air masses and turbidity coefficients

Filter	OG1				RG2				RG8			
Turbidity \ Airmass	1	2	3	4	1	2	3	4	1	2	3	4
0.00	1815	1605	1396	1256	1675	1536	1466	1396	1396	1326	1326	1256
0.05	1605	1256	977	768	1536	1326	1117	977	1326	1187	1047	977
0.10	1396	977	698	489	1396	1047	838	628	1187	977	838	698
0.20	1117	628	349	209	1187	768	419	279	1047	698	489	349

Where the filter is used in addition to a protective window of quartz or other suitable material, the filter factor derived from the measured transmittance must be reduced by 1 per cent to allow for the effects of multiple reflection between the filter and the window.

When measurements of solar radiation behind these standard filters are published, the individual values of the wave-length of the centre of lower cutoff and the filter factor should be stated if known. For this purpose the centre of lower cutoff may be regarded as corresponding to a transmittance of 0.45 (i.e. transmission practically 50 per cent).

For supplementary information reference may be made to pages 398 to 401 of the IGY Instruction Manual (CSAGI, 1958); the value of the Davos reduction factor, DR, discussed in the manual is limited in its use.

9.5 Measurement of the global radiation from sun and sky on a horizontal surface

9.5.1 *General*

Pyranometers for the measurement of the global and sky radiation are exposed continually in all weathers and must therefore be robust in design and securely installed so that even the strongest wind will not appreciably affect the level of the horizontal surface. They must be able to resist the corrosive effects of damp air (especially near the sea); the receiver should either be hermetically sealed inside its glass casing or the casing must be easily removable so that any condensed moisture can be removed and the glass surfaces cleaned. Where the receiver is not permanently sealed inside its protective envelope a desiccator is usually fitted in the base of the pyranometer.

9.5.2 *General precautions*

Pyranometers in continuous operation should be inspected at least once per day, and preferably more frequently, for example when the routine meteorological observations are made. At the inspections, the exposed envelope of the pyranometer should be wiped clean and dry; if frozen snow, glazed frost, hoar frost or rime is present, an attempt should be made to remove the deposit at least temporarily — see page 389 of the IGY Instruction Manual (CSAGI, 1958). The trace on the automatic recorder should be marked and an appropriate note added on the chart for reference when the record is evaluated, which should be done only when the glass hemisphere is known to have been free from deposit. All other temporary interruptions of the record, e.g. for the periodic standardization of the pyranometer, should also be noted. Desiccators should be kept charged with active material.

At stations in areas where severe sandstorms or hailstorms occur, a simple cover can be used to protect the glass envelope of the pyranometer from damage. This cover should be placed over the pyranometer and securely fastened at what is judged to be the onset of a heavy storm. During a season when such storms are likely to occur at night, the cover should be put on after sunset and removed before sunrise the next morning, or as early as possible thereafter. These precautions are especially important in the case of rather fragile instruments such as the Eppley 180° pyranometer (see below). The Moll-Gorczynski pyranometer (see below) is much more robust and even in heavy hail-storms such precautions are rarely necessary.

Some thermoelectric radiometers, in particular the Moll-Gorczynski type, show a difference between the electrical zero position and the zero found when radiation is suddenly cut off (zero depression), especially when the sky radiation only is measured.

9.5.3 *Exposure of pyranometer and correction of record for obstruction*

The site for the pyranometer should be free from any obstructions above the plane of the sensing element and, at the same time, should be readily accessible. If it is impracticable to obtain such an exposure, the site selected must be as free from obstructions (artificial as well as natural) as possible, especially (in the northern hemisphere) from east-north-east, through south, to west-north-west and (in the southern hemisphere) from east-south-east, through north, to west-south-west. If practicable, the pyranometer should be so located that a shadow will not be cast on it at any time (for example, by radio masts or anemometer towers). If it is at all possible, the site should be so chosen that the elevation of any obstruction at azimuths between those corresponding to earliest sunrise and latest sunset should not exceed 5°. Care should be taken that it is not near light-coloured walls or other objects likely to reflect sunlight onto it and that it is not exposed to artificial radiation sources.

At most stations a flat roof provides the best location for mounting the stand for the pyranometer ; if such a site cannot be obtained, a rigid stand with horizontal top surface some distance from buildings and other obstructions should be used.

On the initial installation of a pyranometer, whenever its location is changed, and if a significant change occurs in regard to any surrounding obstructions, the angular elevation above the plane of the receiving surface of the pyranometer and the azimuth of all obstructions throughout the full 360° around the pyranometer should be observed. The altitude above M.S.L. of the pyranometer (i.e. altitude of station + height of pyranometer above ground) and its geographical co-ordinates should be determined.

Should there be obstruction to the direct solar beam (this is readily detected on the charts on cloudless days), the trace should be corrected, wherever this can be done with reasonable confidence, prior to the evaluation of the record.

Correction for obstruction to the sky component of the measured global radiation can only be attempted when there are separate records of global and sky radiation. The procedure is to correct the sky radiation record first and then to adjust the global radiation record. The fraction of the vertical component of the short-wave flux from the sky which is lost by obstruction is to be computed, not the fraction of sky obscured by the obstruction. It will therefore be apparent that radiation incident at angles of less than 5° to the horizon makes only a very small contribution to the total. As a horizon limited by a circular fence with an elevation of 5° diminishes the flux by only 1 per cent, such an effect can normally be neglected. It must be borne in mind that all obstructions (except those completely black) can reflect some solar radiation to the receiver, especially where the object is fairly light in colour, for example, when there is snow cover.

For determining corrections for the loss of sky radiation by obstacles, account should properly be taken of the variation in intensity of the diffuse radiation over the hemisphere of sky which, naturally, depends upon the conditions of the sky at the time. The only practical procedure for determining such corrections is however to assume that the radiation is the same from all parts of the sky. Such procedures are outlined on pages 412 to 413 of the IGY Instruction Manual (CSAGI, 1958).

9.5.4 *Installation*

All electrical connexions should be soundly made and fully weatherproofed. Cables and leads must be firmly attached to the mounting to minimize breakages in windy weather.

All instruments must be correctly levelled so that the receiving surface is truly horizontal. It is strongly recommended that this should be confirmed by means of a circular spirit level (or a pair of crossed levels) attached permanently to the instrument. The adjustment of the level itself should be checked in the laboratory by mounting the instrument on a stand that can be rotated about an axis that is accurately vertical and which passes through the centre of the receiving surface. The instrument is then illuminated by a lamp so that the radiation falls at an elevation of about 15° to the horizontal; the lamp should be run from a constant voltage supply. The output from the radiation instrument is then measured at various azimuths and the level of the instrument adjusted independently of that of the rotating stand until the least possible variation is obtained as the instrument is rotated about the vertical axis. Once this has been done the spirit level is adjusted to read correctly and then locked in position.

Ideally there should be no change in sensitivity with azimuth, but in practice this cannot be achieved and the effect is greater for pyranometers which incorporate a thermopile which is not circular. The orientation of the instrument used should be carefully noted and any local instructions in this matter should be carefully followed.

9.5.5 *Description of suitable instruments*

9.5.5.1 *Moll-Gorczynski pyranometer*

The Moll-Gorczynski pyranometer is a thermopile instrument, in which the receiving surface is covered by two concentric ground and polished glass hemispherical domes, 2 mm in thickness. The outer dome is removable and can be exchanged with filter domes. In the later models the necessary adjustments for cleaning and maintenance have been much facilitated. As the thermopile surface is rectangular particular attention must be paid to orientation. 98 per cent of complete response to a sudden change takes about 30 seconds. The instrument is subject to zero-depression errors. The temperature coefficient is approximately — 0.2 per cent per °C.

9.5.5.2 *New Eppley pyranometer*

An improved form of Eppley pyranometer is available incorporating temperature compensation of the bismuth-silver thermopile and interchangeable hemispheres of filter glass for spectral measurements of global or sky radiations.

The response time for 98 per cent signal is about 30 seconds.

9.5.5.3 *Eppley (180° pyrheliometer) pyranometer*

The receiving surface of the Eppley pyranometer consists of two concentric silver rings ; the inner one is coated black (Parson's Optical Black Lacquer is now used) and the outer one is coated with white (magnesium oxide). The temperature difference between the two rings is measured with thermojunctions, which are in good thermal contact with the lower surfaces of the ring but are, of course, electrically insulated from them. The whole assembly is hermetically sealed inside a specially blown spherical lamp bulb filled with dry air. The magnesium oxide is a good reflector of solar radiation but is a strong absorber of long-wave radiation. This construction minimizes the effect of long-wave radiation from the glass envelope. The time required for about 98 per cent response to a sudden change is about 30 seconds. The temperature coefficient is approximately — 0.1 per cent per °C.

9.5.5.4 *Volochine pyranometer*

The Volochine pyranometer has a thermopile of different construction to the Moll-Gorczynski instrument, and has, like the new Eppley pyranometer, a circular black flat receiving surface. The 98 per cent response time to a sudden change is about 20 seconds. The temperature coefficient is approximately — 0.1 per cent per °C.

9.5.5.5 *Dirmhirn-Sauberer pyranometer (star pyranometer)*

The Dirmhirn-Sauberer pyranometer uses black and white segments alternatively mounted in the form of a star. The construction and operation of this instrument is discussed by Dirmhirn (1958). The measurement is accomplished similarly to that of the instrument described in section 9.5.5.2. The 98 per cent response time to a sudden change is about 30 seconds. The temperature coefficient is negligible.

9.5.5.6 *Yanishevsky thermoelectric pyranometer*

The Yanishevsky thermoelectric pyranometer uses black and white thermojunctions painted with soot and magnesium, the odd junctions being black and the even junctions white. The set of thermojunctions (overall dimensions 3×3 cm) is covered with a glass hemisphere and kept dry with silica gel. The lower part of the glass is protected with a black shield to eliminate the effect of radiation from the earth's surface. The sensitivity of the instrument is 0.1 mV per mW cm^{-2}. The 98 per cent response time is about 25–30 seconds.

9.5.5.7 *Bimetallic actinographs of the Robitzsch type*

Bimetallic actinographs are widely used as simple self-contained recorders. A mechanical linkage is used to record the temperature difference between a black-coated bimetallic strip exposed to solar radiation and two similar bimetallic strips either painted white or shielded from solar radiation.

Because of the relatively large mass of the bimetallic strips, the response time of the instrument is large (10–15 minutes for 98 per cent response) and the instrument is only suitable for the purpose of obtaining estimates of daily totals. Even for this purpose, because of the difficulties in reducing to reasonable amounts the errors due to variation in azimuth, cosine response and temperature, the accuracy is much less than that of an electrical pyranometer.

There are several improved models available but the errors are still much greater than those of electrical pyranometer types.

9.5.6 *Standardization of pyranometers*

9.5.6.1 *Standardization using a pyrheliometer*

The preferred method of standardizing a pyranometer is by comparison with a primary or secondary standard pyrheliometer using the sun as a source. Measurements are taken on a clear day with pyranometers, firstly of the global solar radiation and then of the diffuse component (by shading the pyranometer with a disc mounted at the end of a slender arm held some distance away). The effect of the vertical component S of the direct solar radiation is obtained by substraction, i.e.

$$S = I \sin h = k(t_h - d_h)$$

where I is the observed direct solar radiation, h is the mean solar elevation, t_h is the instrument output in the unshaded condition, d_h is instrument output in the shaded condition and k is the required instrument constant.

The period of shading must be adequate to enable the pyranometer to take up its true reading: in practice 2–5 minutes may be desirable for a Moll pyranometer but as much as 30 minutes for a bimetallic pyranometer. The principal variations in the results obtained are due to random fluctuations in atmospheric conditions, departures from the cosine law response and changes in ambient temperature. The principal pyranometer at a central observing station should be checked each month whenever possible. The procedure should be carried out several times a day for several days over a range of solar elevation and air temperatures and a mean value extracted.

The shading disc used can be approximately 10 cm in diameter if it is held at 1 metre from the receiver (the glass bulb should however be completely shaded). In this way the angle subtended at the bulb will be roughly equal to that of the aperture of the reference pyrheliometer; this arrangement compensates for the circumsolar sky radiation falling on the pyrheliometer sensing surface.

9.5.6.2 *Standardization using another pyranometer*

One pyranometer can be checked against another by operating both side by side for a few weeks. A selection should be made, from the two sets of record of total radiation, of periods of steady radiation (in cloudless sky as well as in overcast conditions) and the ratio of the outputs found from the chart tabulations. If an integrator is used in conjunction with both instruments it is not necessary to restrict the occasions, and all daily totals can be used.

9.5.6.3 *Calibration of pyranometers using an integrating sphere*

Calibration with an integrating sphere ensures that the radiation field and ambient temperatures can be standardized and any pollution effects removed during the comparison.

The sphere is six feet (1.8 m) in diameter and hinged to open along the equatorial plane. The interior is fitted with a rotatable table with an 18 inch (45.7 cm) diameter top supported centrally by tripod legs. The table holds three pyranometers (Eppley 180° pyrheliometers) during calibration.

Supported below the plane of the table are six 150 watt flood lamps. Filtered air is forced in below the table and out of the top of the sphere at a rate sufficient to prevent an instrument temperature exceeding 10° F (5.6° C) above ambient. All openings in the sphere or sources of illumination are baffled. The interior of the sphere is coated by a highly reflective diffuse paint (Middleton and Sanders, 1953).

The lamps are underrun (90 per cent of nominal voltage) from a voltage source stabilized to 0.1 per cent. Pyranometer output is continuously recorded on a three-channel potentiometric recorder. The internal temperature of the working standard pyranometer is also continuously monitored.

Use of the integrating sphere makes it possible for two men to calibrate a dozen pyranometers in a day against a standard. Experience to date has shown that without exception the calibration is reproducible to better than one per cent accuracy (MacDonald and Foster, 1954).

9.5.6.4 *Standardization at a network station*

At field stations, where carefully preserved working secondary standards (either pyrheliometers or pyranometers) are not available, four methods are available to check the pyranometer:

(*a*) If there is a simultaneous record of direct solar radiation, the two records can be examined for mutual consistency by the method used for direct standardization; this simple check should be applied frequently.

(*b*) If there is a simultaneous record of sky radiation, the two records should be frequently examined for mutual consistency by removing the shadow disc or ring.

(*c*) The record can be verified with the aid of a travelling secondary standard radiometer sent out from the central station of the network or from a nearby station.

(*d*) The pyranometer can be exchanged for a similar one sent out from the central station, to which the original one is returned for re-standardization. Either (*c*) or (*d*) should be done at least once per year.

9.5.7 *Measurement of albedo*

The albedo of a surface (for example, of the ground or of a cloud) may be defined as the ratio of the global radiation from sun and sky reflected by the surface to that incident upon it. The local albedo of, say, a grass lawn or an area of bare earth is determined with a pyranometer mounted so that it may be readily inverted from its normal upward-facing position, care being taken that in the downward-facing position the receiving surface remains horizontal. The mounting should introduce the minimum of obstruction to radiation. A series of exposures to the ground and to the sky, alternately, will provide the value(s) required. If a pair of pyranometers are available, they can be installed horizontally, one receiving the downcoming and one the reflected flux of radiation.

The instrument to be used should be calibrated in the inverted position also as the constants for the same instrument may differ for the two positions.

9.6 Measurement of the sky radiation

For measuring or recording separately the diffuse component of solar radiation, the direct solar rays must be screened from the receiver by an additional masking apparatus. It is in practice quite impossible to screen the sun's disc without in addition preventing a small amount of circumsolar skylight from reaching the radiation-sensing element. Where continuous records are required, the pyranometer will have to be shaded from direct sunlight by a disc (for example, a small circular metal plate) held in the beam by an equatorial mounting device or by a shadow ring mounted on a polar axis. With the first arrangement, which entails the rotation of a slender arm synchronized with the sun's apparent motion, frequent inspection is essential, as spurious records are otherwise difficult to detect. The second method involves less personal attention at the station, but necessitates corrections to the chart tabulations, because of the appreciable screening of diffuse radiation by the shadow ring. The precautions to be taken in the construction and use of screening devices are discussed in a recommendation of the International Radiation Conference of 1954 (IUGG, 1955). Further, since the sky radiation from a cloudless sky may be less than one-tenth of the global radiation, a more sensitive recorder is desirable.

9.6.1 *The shading disc attachment*

The small moving screen should be large enough to prevent direct radiation from falling on the outer glass envelope of the pyranometer, so as to avoid errors of measurement arising from multiple reflections. Its operation requires similar instrumentation and manipulation to that described in section 9.3 for a pyrheliometer installed for the continuous measurement of solar intensity. This type of diffuse pyranometer has been discussed by Dogniaux and Pastiels (1955). The angle(s) subtended by the shading screen on the receiving surface of the pyranometer should conform to the aperture angle(s) of the pyrheliometers used for standardization and for recording the solar intensity.

9.6.2 *The shading ring attachment*

When a shadow ring is employed, it has to be installed in such a way that it can slide freely along a polar axis. The ring can then be set easily when the sun is unobscured ; a scale divided in declination σ of the sun would allow the ring to be adjusted when there is no sun.

The shadow ring stand is easily made. It is available commercially, with a declination calibration, for use with Eppley type pyranometers. In construction, special attention should be paid to checking that the plane of the ring is perpendicular to the sliding bar, which must be parallel to the polar axis within about ¼°. With the Moll-Gorczynski and Eppley pyranometer the width of the shadow ring should be sufficient to shade the optical surfaces under all operating conditions. Where it is not possible to make a shadow ring with dimensions corresponding to the aperture angle of the pyrheliometer used, its diameter should be at least 30 cm. The inner surface of the ring should be painted black, to allow the computation of the correction described in section 9.6.5.

The correct setting of the height of the ring relative to the pyranometer is such that at the equinox the centres of the ring and pyranometer receiving surface coincide. Methods for checking this are given on page 427 of the IGY Instruction Manual (CSAGI, 1958).

The north-south alignment of the polar axis should be done with care. A first close approximation should be made, for example, by means of a theodolite and a distant mark of known bearing. Further small adjustments may be made by observing the shadow cast on the pyranometer near sunrise and sunset when the sky conditions permit; after a few trials, the best position (i.e. the one in which asymmetry of shadow about the receiver is at a minimum) can usually be found.

9.6.3 *Installation of sky radiation equipment*

The exposure requirements for the sky pyranometer are the same as those for a global pyranometer.

If both global and sky radiation are to be measured at the site and the two pyranometers cannot be separated by more than about 1 m, the sky pyranometer should be mounted poleward of the global pyranometer to minimize interference. In polar latitudes a greater separation distance may be needed. The separation of the instruments should in all cases be such that not more than 1 per cent of the sky radiation at the global pyranometer is intercepted by the shadow ring of the sky radiation pyranometer. This can be checked by temporarily removing the ring.

9.6.4 *Standardization of a sky radiation pyranometer*

With the shading disc or ring removed, the pyranometer may be standardized in the same way as a global pyranometer. If it is not easy to remove the ring completely, it may be displaced to admit direct sunlight to the receiver which can then be standardized against a pyrheliometer as described in section 9.5.6.1.

9.6.5 *The shadow-ring correction*

Where the shadow-ring type of pyranometer is used, a correction must be made by increasing the values extracted from the charts to compensate for the sky radiation intercepted by the ring simultaneously with the eclipsing of the sun's disc. As the necessary correction cannot be based wholly upon computation, experiments should be made whenever this is practicable to determine the most appropriate values for the correction. Any practicable computations must assume uniform sky radiation and an ideal receiver. Nevertheless, such computations are a good guide to the magnitude of the required correction. Details of methods to be used are given on pages 428 and 429 of the IGY Instruction Manual (CSAGI, 1958).

9.7 Measurement of solar radiation with a spherical receiving surface

For many problems, especially for the biological aspects of climatology, it may be of interest to know the short-wave radiation falling from the sun and sky and from soil or other reflection on a freely-exposed object such as a plant, a man in open air, etc. This radiation integrated over a spherical surface and over a certain time, such as a day, can be measured by the Bellani spherical pyranometer, formerly called lucimeter. The original model described in 1836 by A. Bellani has recently been greatly modified at the Davos Physical and Meteorological Observatory — see the description and theory of the older type by Prohaska and Wierzejewski (1947), and of the recent model by Courvoisier and Wierzejewski (1954). An account of the instrument and its method of calibration is given on pages 424 and 425 of the IGY Instruction Manual (CSAGI, 1958).

Commercial instruments of this type using water instead of alcohol are also available, but these can only be used at places where the water is not likely to freeze.

The residual air pressure inside these instruments exerts an effect on their response to radiation. Monteith and Szeicz (1960) have shown that with an air pressure of 27–31 mb there is a temperature dependent threshold of radiation energy below which no distillation takes place. The optimum air pressure appears to be very much lower than this. The Davos instruments are scrupulously evacuated before being filled with alcohol.

9.8 Measurement of total (solar and terrestrial) radiation and the net radiation

All radiometers measure the exchange of energy between the receiving surface and its immediate surroundings but with pyranometers and pyrheliometers the conditions are so arranged that the long-wave exchange of radiation is mainly with the case (or glass windows) and is so small that it can be neglected in comparison with the effect of solar radiation. When it is desired to measure the flux of long-wave radiation, the receiving surface must exchange radiation freely with all parts of the appropriate hemisphere. A completely uncovered matt black receiving surface will do this but the convective heat exchange with the air will be very variable. If consistent results are to be obtained the convective heat loss must be made effectively constant.

Four main solutions have been proposed : (i) by providing a cover or window which is transparent to long-wave radiation ; (ii) by providing an artificial convective heat loss which is so great that the effect of a variable natural wind can be neglected (this is usually done by blowing a jet of air over a freely exposed plate) ; (iii) by a compensation method — that is, by introducing a second surface, which is not affected by the radiation (or is affected to a much lesser extent) but which is exposed to identical convective heat exchange conditions as the fully exposed surface, and measuring the energy required to maintain the two surfaces at the same temperature ; (iv) by making the response time of the radiometer very long, so that short-period variations of the convective heat loss are smoothed out, and correcting the instrument readings for the effect of longer term variations in wind speed.

It is also possible to maintain an essentially constant convective heat loss if the aperture is reduced (as in the Linke-Feussner pyrheliometer) — but such an instrument cannot be used to measure directly the total flux through a horizontal surface.

Two main types of instrument can be distinguished in each of the four classes outlined above. In the first place there are net pyrradiometers which measure the net transfer of radiant energy of all types and arriving from all directions through a surface defined by the plane of the instrument. Secondly, there are pyrradiometers, which measure the total (solar and terrestrial) radiation exchange between a hemisphere and the receiving black surface. If the temperature of the receiving surface is known the incoming radiation can be deduced.

The net radiation near the ground is important meteorologically but it is the representative value for a large area that is required. The exposure of the pyrradiometer needs to be chosen with care so that the ground surface in the immediate neighbourhood is representative. In practice it is found that the daily totals of the net radiation do not vary with the type of surface as much as might be expected provided the site has an open exposure and the surface is similar over a reasonable area. There appears to be a certain degree of compensation between the temperature of the earth's surface and, to a lesser extent, the temperature and humidity of the lowest layers, because the variations of these temperatures tend to keep the net radiation constant. This compensation is however only approximate and in general great care should be taken in choosing the site.

9.8.1 *The measurement of terrestrial radiation*

The instruments to measure terrestrial radiation only are fundamentally identical with those described in section 9.8. Since however no means are available to remove the unwanted solar radiation component, the terrestrial radiation can only be measured in the absence of solar radiation (night-time).

9.8.2 *Properties of the receiving surfaces*

It is important that the absorptivity of the black used on the receiver should be as uniform as possible over the whole wave-length range. Near the earth's surface this may be taken as 0.3 μ – 50 μ but for use on aircraft or balloons wavelengths of up to 100 μ are also important. Various evaporated metallic blacks have been shown to be satisfactory but fragile. Black paints are almost essential for freely exposed instruments and must be chosen with care. Parsons' Optical Matt Black Lacquer has been found satisfactory for use near the earth's surface.

The cosine law response for plane surfaces coated with the Parsons' Lacquer is good. Exposed painted surfaces should be washed from time to time to remove dust.

If a freely exposed surface becomes wet or iced during operation a new form of heat exchange (i.e. evaporation) is introduced and this vitiates the readings of a radiometer. There is no cure for this but fortunately the condition can be discovered by careful inspection of the record.

9.8.3 *Instruments for measuring total (solar and terrestrial) radiation and the net radiation*

Most of the instruments used in the past are now beginning to be commercially produced. However, instrumentation in this field is in a stage of active development and so the following descriptions are limited to general principles. References to publications describing some of these instruments now available are given below. Detailed descriptions of the commercially available types may be obtained from the manufacturers.

For an interesting review of the different types of net pyrradiometers reference may be made to a paper by J. P. Funk (1964). It may also be added that international comparisons of these instruments are being made under the auspices of WMO. A study of these data when published will not only enable one to judge the relative merits of the different types of instruments, but also suggest future improvements.

9.8.3.1 *Net pyrradiometers*

Net pyrradiometers divide themselves naturally into two main classes, plate or unshielded net pyrradiometers with two freely exposed receiving surfaces, and window or shielded pyrradiometers with the receiving surfaces protected by curved windows, which are generally hemispherical.

The ventilation of plate net pyrradiometers is provided by an air blower driven by an electric motor; a suitably shaped nozzle directs the air symmetrically over the upper and lower surfaces of the element. A thermopile arrangement measures the temperature differences between the top and bottom surface of the plate. Points requiring special attention in practice are:

(*a*) The ventilation must be uniform over both surfaces of the element. If not the instrument will be asymmetric; that is, the response of the two sides to a given radiation flux will be unequal. This can often be tested by inverting the instrument.

(*b*) The electrical output with zero net radiation flux should be zero. This is tested by placing the instrument in a constant temperature enclosure. Any residual output is probably due to unequal ventilation since in general the air temperature after it has passed through the blower will be different from that of the enclosure about the plate.

In the second class of instrument the receiving surface is covered with a hemispherical window. The material usually used is thin (0.1 mm) polyethylene film (known as Lupolen-H and by other trade names). This has been reported as having an integrated transmission from about 0.3 μ to 100 μ of approximately 85 per cent when new, but there are narrow absorption bands around 3.5 μ, 6.9 μ and 14 μ. Because of the different absorption of the window in the long-wave and short-wave regions the calibration of the instrument differs slightly with wave-length. This is overcome in one particular instrument by applying a thin white strip of magnesium oxide (or similar material) across the element. This reflects short-wave radiation but absorbs long-wave radiation. Absorption of solar radiation in the polyethylene window is also a cause of errors which appear as a variation of sensitivity with wind speed and as an apparent increase of any difference of sensitivity of the black receiver for solar and terrestrial radiation. This absorption also varies with temperature and with time so that the polyethylene windows should be renewed at least every 2–3 months under normal conditions but possibly every month in very dusty conditions.

For detailed descriptions of net pyrradiometers in current use, reference should be made to the original papers (Schulze, 1953 ; Yanishevsky, 1951 ; Funk, 1959 ; Suomi *et al.*, 1954 ; Courvoisier, 1950 ; Macdowall, 1954 and 1955).

9.8.3.2 *Pyrradiometers*

Both types of net pyrradiometer described above can be used as pyrradiometers by shielding one surface of the receiving element from radiation exchange ; the output is then proportional to the incoming radiation on the other side minus the outgoing radiation from the instrument itself, which can be calculated if the instrument temperature and the emissivity of the surface are known. The emissivity will be very close to unity. A thermocouple is usually fitted to enable the temperature of the instrument to be measured ; the cold junction can be placed in a bath of constant and known temperature or, more simply, it can be buried in the earth at a depth of about 1 metre.

The compensation type of pyrradiometer — the Ångström pyrgeometer is a well-known example — can usually be used only at night. The receiving surfaces are thin manganin strips, one set of strips being blackened and the other set gold-plated. As the emissivity of the gilt laminae is very low they assume the air temperature, but the black strips lose heat by radiation and cool down. This cooling is compensated by an electrical heating current through the strips, which is adjusted until the two sets of strips are at the same temperature. The net loss in radiation (outgoing radiation from the strips minus the incoming radiation) is proportional to the square of the current. The incoming downward atmospheric radiation can of course be estimated separately if the instrument temperature is known.

The measurements can be disturbed by the wind and careful zero measurements must be made.

9.8.4 *Installation and maintenance of pyrradiometers and net pyrradiometers*

Very careful precautions must be observed in the installation and maintenance of pyrradiometers and net pyrradiometers. These are outlined on pages 442 to 444 of the IGY Instruction Manual (CSAGI, 1958).

9.8.5 *Standardization of pyrradiometers and net pyrradiometers*

9.8.5.1 *Laboratory methods*

Two laboratory methods are available for standardizing pyrradiometers and net pyrradiometers. In the first the radiometer is exposed to the radiation from a black enclosure kept at a known uniform temperature. This requires many precautions and is not recommended as a routine method ; it does however give useful information about the absorptivity of the receiver in the long-wave region.

In the second method, which is more suitable for routine measurements, a tungsten lamp is used as a source of radiation. The radiation flux at the position of the receiver of the radiometer is determined by a secondary standard pyrheliometer (e.g. Ångström compensation pyrheliometer or a Linke-Feussner pyrheliometer). As it is very difficult to control the amount of long-wave radiation received by the radiometer because of the effect of air currents and surroundings at various temperatures, the radiometer and also the secondary standard pyrheliometer should be placed between glass screens. The temperature of the screens, if well ventilated, should only change very slowly and by periodically shading and unshading the radiometer from the direct lamp radiation the output of the radiometer due solely to the direct short-wave radiation from the lamp can be measured. The front screen may be found to warm gradually when the lamp is unshaded and cool when the lamp is shaded but by suitable extrapolation of the measured outputs the effect of this can be measured and suitable corrections applied.

9.8.5.2 *Field methods*

During a period of steady solar radiation during the day (for example on a clear cloudless day) the shading method as used for the standardization of pyranometers can be used. Alternatively the secondary standard instrument of the same type can be used and the outputs compared.

Another method is to use a Linke-Feussner pyrheliometer to measure the flux of atmospheric radiation on clear days and if the flux of solar radiation is known from the measurements, or if the measurements are made at night (when the solar radiation is zero) then a calibration can be achieved. In cloudless conditions a single measurement in one particular zone of the sky may be sufficient to measure the downward atmospheric radiation component (e.g. a zenith angle of 52 ½° has been shown to be correct for S.E. England). In day-time two measurements with the Linke-Feussner instrument are required, with and without a screen of quartz or other suitable material in front of the opening of the pyrheliometer. Reflection at this quartz screen is eliminated by multiplying these particular readings by 1.08. From the difference the required radiation component can be computed.

9.8.5.3 *Routine checks*

If a pyrradiometer or net pyrradiometer is used for continuous recording or a long series of measurements, checks should be carried out at regular intervals. Proper standardization is best, but failing this some suggestions are made below. It is important to realize that these instruments are still in an early stage of development.

For net pyrradiometers the symmetry should be checked by frequent inversion of the instrument. This is especially important for the ventilated type. If the difference in the readings is more than 2–3 per cent, a change in instrumental characteristics has occurred and should be corrected.

In the absence of a secondary standard pyrheliometer, the readings of the global and sky radiation pyranometers may be used to calculate the normal component of solar radiation. Shading of the receiver of the net pyrradiometer or pyrradiometer may be used to compare the two types of measurement and ensure their mutual consistency.

An alternative arrangement is to have another instrument of the same or similar type which is kept carefully and not used for continuous recording. Comparison of readings with this instrument with the results from the one in routine use can then be used to determine the factor of the routine instrument.

9.8.6 *Accuracy of pyrradiometers and net pyrradiometers*

It is difficult to assess the accuracy likely to be attained in practice with pyrradiometers and net pyrradiometers. It is essential to make regular calibrations and comparisons between different instruments. The main source of error in the ventilated type of instrument appears to be variation in the blackening of the receiving surface and changes in the ventilation rate. With the instruments using a polyethylene hemisphere, it seems important to keep a regular check on the transmission of the "window". This can be done by comparing calibrations using short-wave radiation with calibrations using long-wave radiation. In both types of instrument a careful check on the symmetry of response of both sides of the receiving surface should be made when measuring the net radiation.

9.8.7 *Interpolation procedures in tabulation of pyrradiometer measurements*

When net radiation measurements are interrupted by rain it is sometimes possible to make an estimate of the missing values. At night it can usually be assumed that the net radiation is zero. During the day it has been suggested that the net radiation should be taken as three-quarters of the sky radiation, which is approximately equivalent to assuming an albedo of 25 per cent. The use of this factor is obviously limited to the net radiation over certain surfaces only, but it seems a good approximation for instruments exposed over grass.

9.9 Measurement of daylight illumination

To evaluate electromagnetic radiation as light, use is made of a function of wave-length V_λ (the relative luminous efficiency or relative visibility factor of monochromatic radiation of wave-length λ) by which the radiation energy at each wave-length is weighted in accordance with the luminous effect it produces (Annex 9.A, II.10–010). If the rate of passage of radiant energy through a surface (i.e. the radiant power through the surface) in the wave-length interval $\lambda \pm \frac{d\lambda}{2}$ is $\Phi_{e\lambda} d\lambda$ the luminous flux through the surface is defined to be $K_m \int_0^\infty \Phi_{e\lambda} V_\lambda d\lambda$ where the integral extends over the whole spectrum and K_m is a constant independent of wave-length (Annex 9.A, II.10–020). The values of V_λ, based on several experimental investigations and adjusted so that the maximum value is unity, were adopted internationally in 1924 by the *Commission Internationale de l'Eclairage* (CIE). They may be found for example in the Smithsonian Meteorological Tables (Smithsonian Institution, 1951). The values for high luminance levels (photoptic vision) are the appropriate values. Daylight illumination is measured with a receiver whose relative spectral response is the same as that of the human eye. This may be achieved by using a photosensitive cell together with a matching filter or filters. The relative spectral response of the combination should be checked by the use of a spectrophotometer. The errors in illumination measurement caused by the deviation from the CIE curve should be calculated after assuming several different typical spectral distributions of solar radiation. If necessary a correction must be made.

The instrument must have a good cosine response down to zenith distances of at least 75° and preferably 80° and the temperature coefficient of the cell must be low or some means of keeping the cell temperature constant must be provided. The instrument should be capable of being standardized easily and unless the photosensitive device is hermetically sealed it should be kept dry by means of a desiccant. The bad effects of long-term current drain from the cell may necessitate limitation of the cell illumination to keep the current sufficiently low.

Since a linear output is almost invariably required (for example for integration), it may be ensured by restricting the illumination by suitable optical systems and by a proper choice of the electrical load. In most instruments so far used the daylight is first received on a horizontal disc of translucent and/or diffusing material and the cell-filter combination is exposed only to light from the under surface of the disc. The CIE has been studying this problem for some years, and has published an informal report on the measurement of climatological data necessary for the study of natural daylighting problems (CIE, 1964).

9.9.1 *Standardization of the records*

The most used source of a standard level of illumination is a reliable tungsten filament lamp calibrated in terms of the international standard of photometry. By careful work and using regularly calibrated voltmeters the standard can be reproduced in this way with an accuracy of about $\pm$ 2 per cent.

The lower calibrating levels obtained lead to results which can be reliably extrapolated to natural illumination levels only when the linearity of response has been well checked; and when the effect of any variation across the receiver surface in the intensity of light falling on the diffusing disc has been measured and, if necessary, allowed for. Any correction due to imperfect spectral response of the cell can be incorporated in the calibration factor.

The illumination recorder should be checked regularly in routine use. Absolute checks can be made by means of a secondary standard instrument carefully sited and exposed alongside the permanent recorder for one day or so each month. Alternatively a simple optical bench can be set up on which relative measurements are made. In either case calibration against a standard lamp source should be made at 6-monthly or yearly intervals.

9.9.2 *Types of measurement*

The primary illumination measurement that should be attempted is the intensity on a horizontal surface but, as with solar radiation, measurements of the sky (diffuse) illumination and the direct illumination at normal incidence yield additional useful information.

9.10 The spectral distribution of diffuse and global radiation

In spite of the great interest of agricultural and medical research in the spectral distribution of diffuse and global radiation, the measurement of these components of radiation has not yet entered into meteorological practice because of great technical difficulties in construction and calibration.

9.11 The ultra-violet radiation

Ultra-violet radiation is the most difficult to measure because of its extremely high daily variation both as regards the total intensity in the various subdivisions of the ultra-violet part of the spectrum and as regards the steep decrease of intensity towards the shorter wave-lengths. No type of instrument with clearly reproducible conditions (sensitivity, long-wave cutoff, linearity, etc.) is yet available.

9.12 Methods of recording duration of sunshine

9.12.1 *General*

The chief purpose of sunshine recorders is to enable the hourly or daily totals of the duration of sunshine to be measured accurately to the nearest tenth of an hour. Four main types of instrument are available: (*a*) the Campbell-Stokes pattern, which uses the focused heat radiation from the sun to burn a trace in a chart; (*b*) the Marvin pattern, in which the heat radiation actuates a thermometric switch controlling a chronograph pen; (*c*) the Jordan pattern, in which the actinic radiation from the sun is made to record a trace on photographic paper; and (*d*) the Foster photoelectric sunshine switch. Detailed descriptions of these instruments are to be found in the textbooks; only the more essential features are dealt with here. Types (*a*) and (*c*) act as sundials and require no clock.

An examination of published values of duration of sunshine will show that differences of up to 20 per cent in monthly totals can be explained by the use of different types of instruments and recording paper and by the methods used for measuring the records. To make it possible to reduce these values to a common standard, it was decided in 1962 to adopt the Campbell-Stokes recorder as described below as a standard of reference, known as the interim reference sunshine recorder (IRSR). It is recommended that all values of duration of sunshine should be reduced to this standard in future. When this has been done, the tables should include an appropriate note to this effect; for example it could be stated that "these published values have been reduced to the IRSR standard". Alternatively, a note should be included stating that "in order to reduce the values to the IRSR standard the values should be increased (decreased) by x per cent". The reduction factor should be determined by a careful comparison over a period of several months between the national standard and the IRSR. It is considered that by this means it should be possible to achieve international uniformity to within $\pm$ 5 per cent for systematic differences.

It would be very useful to be able to define a precise lower threshold limit of the intensity of direct solar radiation for measurements of bright sunshine, but this is unfortunately not practical. The IRSR corresponds roughly to an *average* lower limit of 21 $mW\,cm^{-2}$. The actual limits depend on a number of factors including the atmospheric turbidity and the moisture content of the card; under extreme conditions a measurable record will be obtained with an intensity as low as 7 $mW\,cm^{-2}$ while under the other extreme an intensity of 28 $mW\,cm^{-2}$ may be necessary. This question has been thoroughly investigated by Bider (1958) and other authors.

9.12.2 *Campbell-Stokes sunshine recorder*

9.12.2.1 *Chief requirements*

The Campbell-Stokes sunshine recorder consists essentially of a glass sphere about 10 cm in diameter mounted concentrically in a section of a spherical bowl, the diameter of which is such that the sun's rays are focused sharply on a card held in grooves in the bowl. The method of supporting the sphere differs according to whether the instrument is required for operation in polar, temperate or tropical latitudes. Three overlapping pairs of grooves are provided in the spherical segment to take cards suitable for different seasons of the year. If comparable results are to be obtained it is necessary that both the spherical segment and the sphere should be made with great precision and that the mounting be so designed that the sphere can be easily and accurately centred in it.

The chief requirements of the sphere are that it should be of uniform and well annealed colourless or very pale glass. For a standard pattern instrument in which the radius of the spherical segment is approximately 73 mm the principal focal length of the sphere for sodium D light should be approximately 75 mm. These figures correspond to an index of refraction of 1.52 ± 0.02. Special equipment is used for testing sunshine spheres (Bilham, 1929). It is recommended that similar equipment, a description of which is available from the British Meteorological Office, be installed at the headquarters of meteorological services that use the Campbell-Stokes recorder.

The spherical segment should be constructed of a durable material such as gun-metal and should have a central line engraved transversely across its inner surface (to facilitate adjustment). There should be provision for adjusting the spherical segment to suit the latitude of a station. To facilitate making adjustments for level and azimuth after the base has been fixed to a rigid support, it is very desirable that the spherical segment and the sphere support should be mounted on a sub-base with screw and slot adjustment.

A recorder to be used as an IRSR should comply with the detailed specifications issued by the British Meteorological Office. All IRSRs should be certified by the British Meteorological Office.

9.12.2.2 *Record cards*

Record cards should be made of a good quality pasteboard which does not expand appreciably in length on wetting. They should be printed in a colour, such as a medium shade of blue, that absorbs solar radiation. The width of the cards should be accurate to within $\pm$ 0.3 mm to avoid difficulties in fitting or retaining them in the grooves of the spherical segment especially in wet weather. Three sizes are used according to the season of the year, as follows :

(*a*) Long curved cards in summer;

(*b*) Short curved cards in winter;

(*c*) Straight cards at equinoxes.

The following detailed specifications apply to cards used with the IRSR.

The thickness of the card should be 0.4 ± 0.05 mm, changes in any dimension with humidity should not exceed 2 per cent, and the colour should be such that no difference from the standard medium blue can be detected by the naked eye when viewed in diffuse daylight. The hour lines should be printed in black.

The nature of the paper and the methods of manufacture, colouring and impregnation should comply with the detailed specifications issued by the French Meteorological Office. The cards should be certified by the French Meteorological Office.

9.12.2.3 *Adjustments*

In installing the recorder the following adjustments are necessary :

(*a*) The base must be levelled ;

(*b*) The spherical segment should be adjusted so that the centre line of the equinoctial card lies in the celestial equator (the scale of latitude marked on the bowl support facilitates this) ;

(*c*) The vertical plane through the centre of the sphere and the noon mark on the spherical segment must be in the plane of the geographic meridian.

A recorder is best tested for (*c*) by observing the sun's image at the local apparent noon ; if the instrument is correctly adjusted the image should fall on the noon mark of the spherical segment or card.

9.12.2.4 *Errors of adjustment*

If all the adjustments have been made satisfactorily the burns should be parallel to the central lines of the cards. Faulty adjustment may cause serious loss of record, at certain times of the year, through the trace running off the edge of the card. A symmetrical trace which is not parallel to the central line indicates faulty adjustment for latitude. An unsymmetrical trace is caused by incorrect meridian adjustment and by incorrect levelling. A trace which is in the correct position at the equinoxes but not parallel to the central line at other seasons indicates a displacement of the centre of the sphere in the plane through the celestial equator. Poor adjustment for concentricity will cause the trace to be broad and ill-defined at the edges.

9.12.2.5 *Measurement of the records*

In order to obtain uniform results from Campbell-Stokes recorders, it is especially important to follow closely the following directions for measuring the records of IRSRs. The daily total of duration of bright sunshine should be determined by marking off on the edge of a card of the same curvature the lengths corresponding to each mark and by measuring the total length thus obtained along the card at the level of the recording to the nearest tenth of an hour. The evaluation of the record should be made as follows :

(*a*) In the case of a clear burn with round ends, the length should be reduced at each end by an amount equal to half the radius of curvature of the end of the burn ; this will normally correspond to a reduction of the overall length of each burn by 0.1 hour ;

(*b*) In the case of circular burns, the length measured should be equal to half the diameter of burn. If more than one circular burn occurs on the daily record it is sufficient to consider 2 or 3 burns as equivalent to 0.1 hour of sunshine; 4, 5, 6 burns as equivalent to 0.2 hour of sunshine; and so on in steps of 0.1 hour;

(*c*) Where the mark is only a narrow line, the whole length of this mark should be measured, even when the card is only slightly discoloured;

(*d*) Where a clear burn is temporarily reduced in width by at least a third, an amount of 0.1 hour should be subtracted from the total length for each such reduction in width, but the maximum subtracted should not exceed one half of the total length of the burn.

In order to assess the random and systematic errors made while evaluating the records and to ensure the objectivity of the results of the comparison, it is recommended that the evaluations corresponding to each one of the instruments compared be made successively and independently by two or more persons trained in this type of work (Levert, 1961).

9.12.3 *Jordan sunshine recorder*

The Jordan sunshine recorder consists of two semi-cylindrical cameras each having, in its flat side, an aperture through which the sun's rays are admitted. The cameras are mounted side by side, one with its aperture towards the east and the other towards the west, on a levelling base plate which can be adjusted for latitude by means of a graduated arc. The record is obtained on photographic paper, such as the ferro-prussic type, placed round the cylindrical wall of each camera. The instrument requires adjustment for level and meridian as well as for latitude. It has been found that measurements of the records are open to considerably more uncertainty than are the measurements of Campbell-Stokes records. One of the difficulties associated with the instrument is that of ensuring constant sensitivity of the photographic paper.

9.12.4 *Marvin sunshine recorder*

The Marvin sunshine recorder is essentially a differential air thermometer with one clear bulb and one black bulb in an evacuated glass jacket. The bulbs are separated by a column of mercury and alcohol that closes an electric circuit when sufficient radiation falls on the instrument. The circuit can be made to operate a chronograph and thus the instrument has the advantage over the Campbell-Stokes and Jordan types of being remote recording.

The Marvin instrument should be set in the meridian plane at such an angle that the mercury column just closes the electric circuit during the time when the sun's disc can be just faintly seen through the clouds. This adjustment should be made in spring or winter, but it does not provide an exact standard for the comparison of different instruments of the same type. Like the Campbell-Stokes instrument, the Marvin is subject to errors due to faulty installation and adjustment and does not record weak sunlight when the sun is within 5° of the horizon. It is affected by diffuse radiation as well as by direct solar radiation.

9.12.5 *The Foster sunshine switch*

The Foster sunshine switch is essentially a difference instrument sensing radiation by means of a shaded and an unshaded photovoltaic cell, both mounted inside a translucent tube supported by a simple equatorial mount which allows seasonal adjustment. A shading band concentric to the translucent tube protects one cell from direct sunlight. The differential output increases during periods of sunshine sufficiently to activate a relay which in turn is used to mark on a recorder or totalizer the duration of sunshine in one minute units. The lag of the instrument is negligible and its sensitivity allows reliable measurements at dawn and dusk.

9.12.6 *Exposure of sunshine recorders*

Two essentials for correct exposure of sunshine recorders are (*a*) that the site should provide an uninterrupted view of the sun at all times of the year, throughout the whole period when it is above the horizon, and (*b*) that the recorder should be firmly fixed to a rigid support. With regard to (*a*), since sunshine is rarely bright enough to be recorded when the sun's altitude is less than 3°, obstructions subtending less than this angle vertically can be disregarded. Where a satisfactory exposure cannot be obtained at ground level it may be desirable to install the recorder on the roof of a building. To determine what effect will be produced by obstructions a survey should be made of their bearings, elevations and angular widths. The proportion of possible sunshine they would cut off can then be calculated by the methods of spherical astronomy.

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ANNEX 9.A

(see paragraph 9.1.1)

Terminology of radiation quantities and measuring instruments

Part I

Basis of the terminology

In preparing a terminology it is first necessary to define the fundamental concepts involved in a manner consistent with the established usage of other branches of science. The basis of the present document is the *International Lighting Vocabulary* 2nd Edition, Volume I (ILV) of the International Commission on Illumination (CIE). In particular, Part II – *Definitions, Quantities and Units*, follows the ILV very closely. There are some aspects of the ILV which are not generally accepted in all branches of physics, notably the recommended symbols, which are more convenient for photometry than for the energetic aspects of radiometry with which physicists in general and meteorologists in particular are more concerned. In Part II the symbols set out are those given in the ILV, although they are in some respects inconsistent with the symbols in Part III. It is considered that there is in fact little danger of confusion, but suitable wording of the context may be necessary in some instances where a symbol (e.g. Q) is used in a sense other than that of the ILV.

In Part III the more frequently used radiation fluxes per unit area are defined after a subdivision of the radiation according to its origin and wavelength. A finer spectral subdivision of the radiation has not been attempted because there is as yet no agreement between different international organizations ; such a subdivision is in practice used mainly by biologists.

In Part IV the main types of radiation instruments are defined. In the past there has been much confusion because similar instruments have been called by different names and the same name has been used for different instruments. It is hoped that in the future such unnecessary trouble can be avoided.

Different units are in common use for meteorological radiation measurements. It is however desirable to employ internationally adopted units. In particular the joule should be used for radiant energy and the watt for radiant flux ; in general units of the MKS System should be used, rather than auxiliary units such as the calorie, the BTU and the langley. The conversion factors between these different units of the radiation flux per unit area and of its temporal sum are tabulated in the appendix. They are calculated from the international units adopted in 1952 by the British Standards Institute and in 1959 by the Deutscher Normenausschuss (DIN 1301).

Part II

Definitions, quantities and units

International Lighting Vocabulary reference	*Quantity*	*Definition*	*Symbol in ILV*	*Unit*
(1)	(2)	(3)	(4)	(5)
05–005	Radiation	Electromagnetic energy, emitted, transferred or received.		
05–135	Radiant energy (radiation)	Quantity of energy transferred by radiation.	Q_e	Joule (J) $\equiv 10^7$ erg
05–140	Flux of radiation, radiant flux, radiant power	Power emitted, transferred, or received in the form of radiation.	$\Phi_e = \frac{dQ_e}{dt}$	Watt (W)
05–150	Intensity, radiant intensity (of a source, in a given direction)	The quotient of the radiant power emitted by a source, or by an element of source, in an infinitesimal cone containing the given direction, by the solid angle of that cone. N o t e : For a source which is not a point source: The quotient of the radiant flux received at an elementary surface by the solid angle which this surface subtends at any point of the source, when this quotient is taken to the limit as the distance between the source and the source is increased.	$I_e = \frac{d\Phi_e}{d\omega}$	W per unit solid angle

(1)	(2)	(3)	(4)	(5)
05–155	Radiance Radiant intensity per unit area (at a point of a surface, in a given direction)	The quotient of the radiant intensity in the given direction of an infinitesimal element of the surface containing the point under consideration, by the area of the orthogonal projection of this element on a plane perpendicular to the given direction.	$L_e = \frac{d^2\Phi_e}{dA \cos \epsilon \, d\omega}$	Wm^{-2} per unit solid angle
05–160	Irradiance Flux of radiation per unit area (at a point of a surface)	The quotient of the flux of radiation incident on an infinitesimal element of surface containing the point under consideration, by the area of that element.	$E_e = \frac{d\Phi_e}{dA}$	Wm^{-2}
05–165	Irradiation (at a point of a surface)	The time integral of irradiance.	$D_e = \int E_e dt$	$J\ m^{-2}$
05–170	Emittance, radiant emittance (from a point of a surface)	The quotient of the flux of radiation emitted by an infinitesimal element of surface containing the point under consideration, by the area of that element.	$M_e = \frac{d\Phi_e}{dA}$	$W\ m^{-2}$
05–185	Special density (concentration) of a radiometric quantity	Quotient of this quantity, taken over an infinitesimal range on either side of a given wave-length (or frequency) by the range. N o t e : Frequencies, wave-numbers or their logarithms may also be used ; if there is a risk of ambiguity this should be avoided by means of the wording : "spectral concentration in terms of frequency" etc.	$X_e(\lambda) = \frac{dX_e}{d\lambda}$	

(1)	(2)	(3)	(4)	(5)
25–110	Light	(1) Attribute of all the perceptions or sensations which are peculiar to the organ of vision and which are produced through the agency of that organ. (2) Radiation capable of stimulating the organ of vision.		
10–010	Relative luminous efficiency (of a monochromatic radiation of wave-length λ)	The ratio of the radiant flux at wave-length λ_m to that at wave-length λ which produces equally intense luminous sensations under specified photometric conditions, λ_m being chosen so that the maximum value of this ratio is unity. Unless otherwise indicated, the values used for the relative luminous efficiency relate to photopic vision by the normal eye having the characteristics laid down by the International Illumination Commission (CIE).	V_λ	
10-020	Luminous flux	The quantity characteristic of radiant flux which expresses its capacity to produce a luminous sensation, evaluated according to the values of relative luminous efficiency. Unless otherwise indicated, the luminous flux in question relates to photopic vision, and is connected with the radiant flux in accordance with the formula adopted in 1948 by the CIE, i.e. by the relation $\Phi = K_m \int \Phi_{e\lambda} . V_\lambda . d\lambda$	I, F	lumen (lm) =the luminous flux per unit solid angle from a point source having an intensity of one candela.

(1)	(2)	(3)	(4)	(5)
10–020 (contd)		in which $\Phi_{e\lambda}.d\lambda$ is the radiant flux corresponding to the radiation comprised between λ and $\lambda + d\lambda$ and V_λ is the relative luminous efficiency, the values of which as a function of λ are given above. Applied to the radiation of a full radiator at the temperature of solidification of platinum, the formula determines the value of $K_m(lm.W^{-1})$.		
10–065	Luminous intensity (in a direction)	The quotient of the luminous flux emitted by a source, or by an element of a source, in an infinitesimal cone containing the given direction, by the solid angle of that cone.	$I = \frac{d\Phi}{d\omega}$	Candela (cd). The luminance of a full radiator (black body) at the temperature of solidification of platinum is 60 cd cm^{-2}
10–085	Luminance (at a point of a surface, in a direction)	The quotient of the luminous intensity in the given direction of an infinitesimal element of the surface containing the point under consideration, by the orthogonally projected area of the element on a plane perpendicular to the given direction.	L, B	cd m^{-2}
10–095	Illumination (at a point of a surface)	The quotient of the luminous flux incident on an infinitesimal element of surface containing the point under consideration by the area of that element. N o t e : The analogy is to irra*diance* not to irradiation.	$E = \frac{d\Phi}{dA}$	lux (lx) ($\equiv$ lm . m^{-2})
10–110	Quantity of illumination	The product of an illumination and its duration. N o t e : The analogy is to irradiation.	$Q_E = \int E\, dt$	lux second lx.s

(1)	(2)	(3)	(4)	(5)
10–120	Luminous emittance (from a point of a surface)	The quotient of the luminous flux emitted from an infinitesimal element of surface containing the point under consideration, by the area of that element.	$M = \frac{d\Phi}{dA}$	$lm\ m^{-2}$
10–125	Spectral concentration (density) of a photometric quantity	The quotient of this quantity taken over an infinitesimal range of wave-length containing a given wave-length, by the range. Note : Frequencies, wave-numbers or their logarithms may also be used ; if there is a risk of ambiguity this should be avoided by means of the wording : "special concentration in terms of frequency" etc.	$X_\lambda = \frac{dX}{d\lambda}$	

Part III

Meteorological radiation quantities

(The designations which are within brackets are possible alternatives)

No.	*Quantity* (1)	*Definition* (2)	*Symbols* (3)	*Remarks* (4)
1	*General designations*			
1.1	Radiation	Electromagnetic energy, emitted, transferred or received.		In French "radiation" is used for monochromatic radiation and "rayonnement" for polychromatic radiation.
1.2	Subdivision of the meteorological significant radiation according to its origin.			
1.2.1	Solar radiation	Radiation emitted by the sun.		
1.2.2	Terrestrial radiation	Radiation emitted by the planet earth.		The expression "terrestrial radiation" hitherto used by meteorologists is now changed to "terrestrial surface radiation". This change is necessitated by the use of the expression "terrestrial radiation" in space science as signifying the planetary radiation from the earth and its atmosphere.
1.2.2.1	Terrestrial surface radiation	Radiation emitted by the surface of the earth.		
1.2.2.2	Atmospheric radiation	Radiation emitted by the atmosphere.		

No.	(1)	(2)	(3)	(4)
1.2.3	Total radiation	Solar and terrestrial radiation.		Frequently subdivided for convenience in meteorology into: (a) short-wave radiation (wavelengths less than approximately 4 μm); and (b) long-wave radiation (wavelengths greater than approximately 4 μm).
2	*Classification of the vertical components of the meteorologically significant radiation fluxes per unit area (i.e. of the irradiance of horizontal surfaces) according to the origin and the direction of the radiation flux.* For inclined or vertical surfaces the quantities given in 2 have the same designations as are proposed for horizontal surfaces; but the orientation of the surface shall be given (e.g. global radiation on a surface inclined at 30° to the south).			
2.1	Downward radiation	Downward solar and downward atmospheric radiation.	Q↓	Q↓ = K↓ + L↓
2.1.1	Global solar radiation (formerly total radiation)	Downward direct and diffuse solar radiation as received on a horizontal surface from a solid angle of 2 π.	K↓	K↓ = S + D
2.1.1.1	Vertical component of direct solar radiation	Solar radiation coming from the solid angle of the sun's disc, as received on a horizontal surface.	S	S = I cos Z = I sin h z = sun's zenith angle h = sun's altitude (I : see 3.1)
2.1.1.2	Sky radiation (diffuse solar radiation)	Downward diffuse solar radiation as received on a horizontal surface from a solid angle of 2 π with the exception of the solid angle subtended by the sun's disc.	D	

No.	(1)	(2)	(3)	(4)
2.1.2	Downward atmospheric radiation	Downward long-wave atmospheric radiation, mainly emitted by the atmosphere.	L↓ (A↓)	L↓ = A↓
2.2	Upward radiation	Upward solar, terrestrial surface and atmospheric radiation.	Q↑	Q↑ = K↑ + L↑. L↑ includes also L_g the long-wave radiation emitted by the earth's surface.
2.2.1	Reflected solar radiation (reflected global radiation)	Upward solar radiation reflected by the earth's surface and diffused by the atmospheric layer between the ground and the point of observation.	K↑ (R)	(R) is the upward solar radiation reflected by the earth's surface alone.
2.2.2	Upward terrestrial radiation	Upward terrestrial surface and long-wave atmospheric radiation.	L↑	L↑ is the sum of components of (1) surface emission; (2) long-wave radiation reflected by the surface; and (3) upward atmospheric radiation as received at the level of observation.
2.2.2.1	Upward terrestrial radiation surface	Terrestrial surface radiation as measured at the surface of emission.	Lg	
2.2.2.2	Reflected atmospheric radiation	Upward long-wave radiation reflected by the earth's surface.	r	
2.2.2.3	Upward atmospheric radiation	Upward long-wave atmospheric radiation.	A↑	
2.3	Net radiation	Net flux of downward and upward total (solar, terrestrial surface, and atmospheric) radiation; net flux of all radiations.	Q*	Q* = Q↓ — Q↑ Q* = K* + L*
2.3.1	Net solar radiation	Net flux of downward and upward solar radiation.	K*	K* = K↓ — K↑

No.	(1)	(2)	(3)	(4)
2.3.2	Net terrestrial radiation	Net flux of atmospheric and terrestrial surface radiation.	L^*	$L^* = L\downarrow - L\uparrow$
3	*Other meteorologically significant radiation fluxes per unit area*			
3.1	Direct solar radiation	Solar radiation coming from the solid angle of the sun's disc on a surface perpendicular to the axis of the solid angle.	I	
3.1.1	Solar constant	Solar radiation (as defined in III 3.1) received on a surface perpendicular to the solar beam outside the earth's atmosphere when the earth is at its mean distance from the sun.	I_0	
3.2	Downward effective radiation	Net radiation on a horizontal, upward-facing black surface at the ambient air temperature.	$Q_{eff}\downarrow$	$Q_{eff}\downarrow = Q\downarrow - \sigma T_a^4$ σ = Stefan-Boltzmann constant T_a = air temperature
3.3	Upward effective radiation	Net radiation on a horizontal, downward-facing black surface at the ambient air temperature.	$Q_{eff}\uparrow$	$Q_{eff}\uparrow = Q\uparrow - \sigma T_a^4$
3.4	Radiation is also sometimes measured with instruments which do not have plane receiving surfaces (e.g. spherical, cylindrical); the following radiation fluxes per unit area (of the surface) on a spherical receiver can be distinguished.			
3.4.1	—	Total solar, atmospheric and terrestrial surface radiation received on a spherical surface.	Q_S	$Q_S = K_S' + L_S$
3.4.2	—	Solar radiation received on a spherical surface.	K_S	
3.4.3	—	Terrestrial radiation received on a spherical surface.	L_S	

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Part IV

Meteorological radiation measuring instruments

No.	*Instrument* (1)	*Definition* (2)	*Remarks* (3)
1	Radiometer	Instrument for measuring radiation.	When any of these instruments is used with a recorder, the suffix "-meter" may be replaced by "-graph" to indicate the complete equipment.
2	*Instruments mainly used for measuring the downward and upward radiation fluxes per unit area (radiant flux density) and their differences.*		Instruments of this kind are mainly used with horizontal upward-facing receiving surfaces. In all other cases the direction shall be specified in the description of the measuring device.
2.1	Pyrradiometer	Instrument for measuring total radiation (solar and terrestrial) falling from the solid angle 2π on a plane surface (mainly to measure quantities defined in III 2.1 and III 2.2).	
2.2	Pyranometer	Instrument for measuring solar radiation falling from the solid angle 2π on a plane surface, namely the quantities defined in III 2.1.1 and III 2.2.1 and, with a shading device, the quantities defined in III 2.1.1.2.	
2.3	Pyrgeometer	Instrument for measuring net atmospheric radiation on a horizontal upward-facing black surface at the ambient air temperature.	

No.	(1)	(2)	(3)
2.4	Net pyrradiometer	Instrument for measuring the net radiation as defined in III 2.3, and possibly its components.	Formerly called balance-meter.
2.5	Net pyranometer	Instrument for measuring the net solar radiation as defined in III 2.3.1, and possibly its components.	
3	*Other radiation measuring instruments*		
3.1	Pyrheliometer	Instrument for measuring direct solar radiation.	See remark under 2.
3.2	Spherical pyrradiometer	Instrument for measuring total radiation (solar, atmospheric and terrestrial surface) received on a spherical surface (to measure the quantity defined in III 3.4.1).	See remark under 2. Similar definitions are possible for other curved surfaces, such as a cylindrical surface.
3.3	Spherical pyranometer	Instrument for measuring the solar radiation received on a spherical surface (to measure the quantity defined in III 3.4.2).	See remark at 3.2.

ANNEX 9.A — Appendix

UNITS AND CONVERSION FACTORS FOR RADIATION DATA

1 Quantity of radiation per unit area

UNITS	$J.cm^{-2}$	$cal.cm^{-2}$	$mWh.cm^{-2}$
$erg.cm^{-2}$	10^{-7}	2.39×10^{-8}	2.78×10^{-8}
$J.m^{-2}$	10^{-4}	2.39×10^{-5}	2.78×10^{-5}
$J.cm^{-2}$	1	0.239	0.278
$kWh.m^{-2}$	360	86.1	100
$mWh.cm^{-2}$	3.6	0.861	1
$cal.cm^{-2}$	4.19	1	1.163
$kpm.m^{-2}$	9.81×10^{-4}	2.34×10^{-4}	2.72×10^{-4}
$BTU.ft^{-2}$	1.136	0.271	0.316

1 joule = 10^7 erg
= 1 W.s (watt-second)
= 1.020×10^{-1} kpm (kilo-pond-metre)
= 2.389×10^{-4} kcal (kilo-calorie)
= 0.9480×10^{-3} BTU (British thermal unit)
= 2.778×10^{-7} kWh (kilo-watt hour)

1 $cal.g^{-1}$ = 1.800 $BTU.lb^{-1}$

p = pond weight of the mass of 1 gm at a place where gravity is 9.8067 $m.s^{-2}$

2 Radiant flux per unit area

UNITS	$mW.cm^{-2}$	$cal.cm^{-2}.min^{-1}$
$erg.cm^{-2}.s^{-1}$	10^{-4}	1.433×10^{-6}
$W.m^{-2}$	0.1	1.433×10^{-3}
$kW.m^{-2}$	100	1.433
$mW.cm^{-2}$	1	0.01433
$cal.cm^{-2}.min^{-1}$	69.8	1
$mcal.cm^{-2}.s^{-1}$	4.19	0.0600
$kpm.m^{-2}.h^{-1}$	2.72×10^{-4}	3.90×10^{-6}
$BTU.ft^{-2}.h^{-1}$	0.316	4.52×10^{-3}
$BTU.ft^{-2}.min^{-1}$	18.9	0.271

NOTE : The internationally recommended units are joule (J), watt (W) and metre (m).

ANNEX 9.B

(see paragraph 9.2.8)

Aperture angle of pyrheliometers

1. The following material is based on a recommendation adopted at the Joint International Radiation Conference at Davos in September 1956.

2. An extensive theoretical examination of the contribution of the circumsolar sky radiation has been made by Dr. R. Pastiels. He has found it convenient to express the results in terms of the following normalized parameters, which specify the aperture conditions of a radiometer. If R is the limiting aperture, r the radius of the receiver, and l the distance between them,

$$a = \frac{R}{r} \qquad \text{and} \quad b = \frac{l}{r}$$

Z_o the "opening angle" $= \tan^{-1}\frac{a}{b}$

Z_p the "slope angle" $= \tan^{-1}\frac{a-1}{b}$

Z_l the "limit angle" $= \tan^{-1}\frac{a+1}{b}$

The calculations have been made for

Z_p = 16′, 30′, 1°, 3°;

b = 3, 7, 10, 15, 20, 25, 50, 100, 500, 1000.

3. The calculations show that if a precision measurement of radiation from the sun's disc alone is required, a correction must be made for the circumsolar radiation. It is not possible to choose practicable values of the parameters (i.e., values which do not require elaborate engineering to keep the instrument directed at the sun) in order to construct a radiometer which will give a circumsolar sky correction as low as 1 per cent for poor sky conditions.

4. The difficulty of the correction lies in the specification of the circumsolar sky radiation. In Dr. Pastiel's work this is specified in terms of two parameters — the first the ratio of the radiance at the centre of the solar disc to that of the sky at the edge of the disc, the second the exponent in an exponential function fitted to the sky radiance measured outwards from the disc.

5. If the sky conditions are specified in this way the correction to normal meteorological measurements may be easily made if the instrument parameters are close to those for which the tables have been computed. For the majority of instruments now in use the value of Z_p is close to 1°.

6. The question of rectangular apertures has been treated in less detail, though the principles of the treatment are the same. Tabulations have been made for the aperture conditions of the Michelson bimetallic pyrheliometer and the Smithsonian type Ångström instruments. If newly constructed instruments have aperture conditions geometrically similar to either of these types the tabulations will be applicable to them. It is of interest to note that to minimize the effect of circumsolar radiation the aperture and receiver should be of square shape, but detailed calculations have not been made for this case.

7. Dr. Pastiels' calculations allow an estimate of the effect of circumsolar radiation in measurements made with the normal silver disc and the original Ångström instruments. In the average sky conditions the Ångström pyrheliometer can be expected to receive sky radiation amounting to two or three per cent of the solar radiation, the silver disc pyrheliometer one half per cent less.

8. It is recommended that pyrheliometers constructed in future should have an angle of slope not less than 1° and not greater than 2° ($1° \leqq Z_p < 2°$) and a ratio of distance between receiver and limiting aperture to radius of receiver equal to or greater than 15 ($b \geqq 15$). These conditions imply that the "opening angle" must not be greater than 4° ($Z_o = \tan^{-1}\frac{R}{l} < 4°$).

ANNEX 9.C

(see paragraph 9.3.8)

Rules for ensuring the required accuracy in pyrheliometer comparisons

1. Maintenance of the international pyrheliometric scale

The international pyrheliometric scale will be represented by a set of at least three standard pyrheliometers belonging to the recognized regional centres and including, if possible, the pyrheliometers representative of the original Stockholm and Washington scales.

2. Reference values for the comparisons

The reference values to be taken for the comparisons will be those corresponding to the mean values given by the above-mentioned instruments after full statistical processing of the series of measurements to determine:

(*a*) The operational reliability of the instruments (intrinsic accuracy of the instrument measurement);

(*b*) The homogeneity of the series (influence of the meteorological factors in relation to the instrument characteristics). Certain series of measurements may perhaps be retained after any necessary corrections have been made.

3. Procedure for comparisons

(*a*) *Pyrheliometers*

The pyrheliometers participating in the comparisons must be duly checked before and after transport to the international centre either by comparison with the regional or national reference pyrheliometers or by application of the similarity and stability tests described by P. Courvoisier (Archiv. Met. Geoph. Biokl. Ser. B., Vol. 12, p. 426, 1963).

(*b*) *Auxiliary electrical equipment*

The milliammeter or potentiometer working with the standard pyrheliometers must have been checked beforehand by the competent national official bodies for errors of scale, linearity and temperature; calibration certificates must be produced. Taking the accuracy required in the value of radiant flux per unit area as 0.4%, the measurement of current should be made with an accuracy of at least 0.2%. The rheostats regulating the heating current should be so designed that, for an incident energy of the order of 100 mW cm^{-2}, the smallest intensity variation obtainable with the rheostat corresponds to a maximum zero galvanometer spot displacement of not more than ½ or 1 scale division.

The procedure followed at the 1964 international comparisons in Davos was that each pyrheliometer is connected to its own auxiliary equipment so that the instruments are read simultaneously and several sets of comparative observations can be taken in quick succession at stated intervals. Another possibility is to connect each of the pyrheliometers in turn to the same auxiliary equipment, thereby eliminating any differences which may arise from the use of different auxiliary equipments. In this case, however, the comparative observations will necessarily be at longer intervals as time will be required to disconnect one pyrheliometer and connect up another. This procedure will be really effective only if, instead of solar radiation which may fluctuate with time, a standard laboratory source of radiation is used.

(*c*) *Galvanometer zero*

The galvanometer zero should be adjusted under the same conditions for all the instruments, either both strips shaded, or both irradiated. High accuracy studies should be made of the influence of these methods on the measurement.

(*d*) *Timing and length of the series*

The procedure of the 1964 comparisons at Davos can be followed, namely 11 simultaneous observations to the series each consisting of readings at minute intervals and the first observation of the series not entering into the calculation; the galvanometer zero to be read before and after each series.

(*e*) *Associated observations*

During the observations, measurements with filters for the calculation of the turbidity factor, measurements of air temperature, wind speed and direction should be made.
Similarly direct solar radiation should be recorded continuously throughout by means of a pyrheliometer with thermocouples and a registering potentiometer of good sensitivity (5 mV full scale) with zero offsetting and adequate registering speed (2 mm min^{-1}).

4. Reduction method

Though according to Davos Observatory internal report No. 206 the comparison of the arithmetical means of the 10 observations of each series gives the same results as the method based on the calculation of the successive moving averages of pairs of observations, it would nevertheless be best to reduce the observations, by the latter method, in order to keep a permanent check on observations and obtain a larger number of values for comparison (8 per series instead of 1).

The final report will be drawn up after full statistical study of the results of the observations.

5. Site for comparisons

The site selected for international comparisons should satisfy the following requirements :

(*a*) It should be located in a climatic region where there are frequent periods of sunshine and clear sky during two consecutive weeks;

(*b*) It should be at a suitable altitude to facilitate the transposing of the international to the national pyrheliometric scale and thus ensure the calibration of the radiometers of the network in the best conditions;

(*c*) It should have installations enabling it to receive about twenty participants and accommodation for them to make their observations;

(*d*) It should provide rapid measurement reduction facilities for participants;

(*e*) It should possess measuring and checking equipment of an accuracy at least equal to that required of the instruments submitted to the comparisons;

(*f*) It should have the necessary facilities and laboratory equipment for checking and maintaining the accuracy of the auxiliary equipment;

(*g*) The staff of the centre should be skilled and should include at least one specialist with wide experience in radiation.

APPENDIX B

Descriptions of Procedures Used by Some of the Calibration Facilities

It should be remembered, when reading the following methods, that many of these procedures are varied from time to time for a variety of different reasons, and that they are continually being improved as each facility and experimenter gain experience. In some cases the procedures were modified as a result of our visit and discussions.

The procedures in this appendix are selected in order to illustrate the variety of approaches used for calibration. No attempt was made to be complete in cataloguing every calibration process performed by each of the organizations included here.

The order is that which was judged would provide the most logical flow of the ideas presented.

The opinions expressed in these descriptions are in most cases those of personnel in these organizations.

THE NOAA/DOE SOLAR RADIATION FACILITY AND MEASUREMENT NETWORK

Edwin Flowers, NOAA/ERL-ARL, Boulder, CO

General Description of Facility Procedures

Purpose (Charter)

The Air Resources Laboratories of the Environmental Research Laboratories, NOAA, with support from the Division of Solar Energy, Department of Energy, has established the Solar Radiation Facility in Boulder, Colorado. Primary functions of the Facility are: (1) to maintain standard instruments; (2) to calibrate pyranometers and pyrheliometers; (3) to test specimen instruments from different manufacturers; and (4) to make radiation measurements and develop interrelationships.

Normal Tasks (Procedure)

Normal procedures include: the daily gathering of data from the multi-position test array designed to analyze the various instrumentation; magnetic tape storage of that data and computer processing; analysis of the output numbers; and fundamental improvements to calibration procedures.

The facility also calibrates pyranometers and pyrheliometers as a service to the public.

Related Tasks (Special Procedures)

Special test procedures and apparatus applications are being designed and continually updated in order to provide more complete information on such topics as:

1. cosine effect, continuous outdoor exposure
2. azimuthal angle in relation to thermopile axis
3. intensity, temperature response.

Funding Agency (Level)

Funds for the facility came initially from the National Science Foundation and subsequently from the Department of Energy.

Number of Personnel

The number of personnel was increased from one to three when the move was made from NOAA, in Washington, D.C., to the new facility in Boulder, Colorado.

Standards Maintained

	Manufacturer and Models
Absolute Insts.	
1. Kendall Pyrheliometer	1. J.P.L. TMI MARK-IV
2. Eppley Pyrheliometer	2. H-F
Pyrheliometer	
1. Eppley	1. Nip
2. Eppley Angstrom	2.
3. Abbot Silver Disc	
Pyranometer - (Relative - Standards)	
1. Eppley	2. Mod. (PSP)
2. Spectrolab	3. Mod. (SP-75)
Other	
1. Campbell-Stokes Sunshine recorder	

Instruments Normally Calibrated

Pyrheliometer (no filter)

1. Eppley NIPS

Pyranometer (no filter)

1. Eppley (8-48), (psp)
2. Spectran (2069)
3. Spectrolab (SR-75)
4. Lambda (658-7607) (Silicon)
5. Matrix-Lab (2484) (Silicon)
6. Kipp-Zonen (752492)
7. Kahl (1292)
8. Hy-Cal (56237)
9. Rho-Sigma (129) (Silicon)
10. Lintronic (S1103A)

Calibration Methods:*

National Oceanographic and Atmospheric Administration/
Solar Radiation Facility
NOAA/ERL-ARL
Boulder, Colorado

Standard Instruments: The primary reference instrument of the facility is the TMI (Kendall) Absolute Cavity Radiometer, serial number 67502, a pyrheliometer with a 5° circular field of view. It is self-calibrating and measures direct beam irradiance in absolute units. It participated in the International Pyrheliometric Comparison held in Davos, Switzerland in October 1975. The results of that comparison gave the ratio between it and the PACRAD III--the standard for the comparisons, as 1.0004.

A second absolute cavity radiometer, an Eppley HF radiometer, was purchased in 1978 and comparisons with the TMI radiometer shows the HF gives irradiance values about 0.3 percent lower than the TMI.

Comparisons of absolute radiometers were held with the Solar Energy Research Institute on two occasions, and in a joint effort with the Desert Sunshine Exposure Test Laboratories (DSETL), International comparisons of absolute radiometers were held in Nov. 1978, May 1979, and Nov. 1979 at DSETL, New River, Arizona.

Secondary reference instruments of the SRF consist of a Smithsonian Silver Disk pyrheliometer and an Eppley-Angstrom compensation pyrheliometer, both of which participated in the 1975 IPC, and an Eppley NIP, serial number 1330. The NIP 1330 which carries the NOAA/NWS version of the International Pyrheliometric Scale-1956, is the only one of this group which is routinely compared with the TMI absolute radiometer. During 1976, the relationship between NIP 1330 and the TMI absolute radiometer formed the basis for adjusting the NOAA/NWS pyranometers from the IPS-1956 to the Absolute Radiation Scale. This ratio between irradiance measurements with NIP 1330(IPS) and TMI(ABS) in 1976 was 0.975 ± 0.005, which means that the Absolute Radiation Scale gives irradiance

*The information in this section is edited from reports about the Solar Radiation Facility (SRF). These reports were prepared by Edwin C. Flowers.

values about 2.5 percent higher than the IPS-1956 as the IPS was maintained by NOAA/NWS. Comparisons between NIP 1330 and the TMI radiometer have been made routinely since 1976. For 53 days of comparison in 1977 the ratio was 0.973 ± 0.004, and for 44 days of comparison in 1978 the ratio was 0.970 ± 0.004. Table 1 presents results of the comparisons of NIP 1330 and also NIP's Eppley 14856 and 14857 with the TMI radiometer during 1978. These three instruments are used as control instruments during every pyrheliometer calibration. In Table 1, C* denotes the derived calibration value and C the accepted value. The accepted value for these instruments was that obtained during 1977. Two measures of variability are given in Table 1, the first for the variation over the year (σ/C*), the standard deviation of a daily calibration value divided by the average calibration value for the year, and the second for the variation within a day (σ/C* day), the standard deviation of a single value within a day divided by the average value for the day. From these data there is no indication of any change of sensitivity of NIPs 14856 and 14857 but there is a hint of a gradual decrease in sensitivity of NIP 1330 (about 0.5 percent) since 1976. These data also give a measure of the degree of comparability that can be expected from Eppley NIPs on the time scales of two years, days within a year and within a day.

Table 1

Pyrheliometer Calibrations
Comparisons with TMI 67502, Boulder 1978

Instrument	Number Days	Number OBS	C* ($x10^{-6}$ V/w-m^{-2})	C*/C	σ/C* (yr/%)	σ/C (day/%)
Eppley 1330	44	5456	2.663	0.9966	±0.38	±0.30
Eppley 14856E6	53	6387	8.076	1.0011	±0.28	±0.21
Eppley 14857E6	56	6758	8.329	1.0000	±0.38	±0.19

Solar Source - Pyrheliometers

All pyrheliometer calibrations at Boulder are done by direct comparison with the Kendall radiometer. Two or three Eppley pyrheliometers (NIPs) are always included in the calibration array as controls. Usually, two or three days are used for a calibration with each day typically consisting of about 100 one-minute comparisons. Each day gives a mean calibration value and a measure of the variation of the one-minute values. The final calibration value is the average of the several days of comparison.

About 80 pyrheliometers were calibrated by the SRF during 1978, including 38 for use in the NOAA solar radiation network.

Table 2 compares calibration values obtained by the SRF with those of the Eppley Laboratory for 65 recently manufactured Eppley pyrheliometers. For the majority of these instruments the SRF calibration was

Table 2

Comparison of SRF and Eppley Pyrheliometer Calibration Factors-Frequency Distribution of Ratio C_{SRF}/C_{EPLAB}*

Ratio C_{SRF}/C_{EPLAB}	Number of Instruments
≤0.949	1
0.950-0.959	1
0.960-0.969	1
0.970-0.979	1
0.980-0.989	3
0.990-0.999	14
1.000-1.009	23
1.010-1.019	11
1.020-1.029	6
1.030-1.039	4
≥1.040	0

*These data are presented here because they illustrate well the accuracies which can be expected from the best calibrations. Both the SRF and Eppley Laboratories are judged to be using good procedures and both are judged to be careful in their work. These data do not illustrate the correctness of procedures at either facility. These instruments are the best available.

done immediately after the Eppley calibration and before the instruments were used for regular observations. The table shows that the median difference between the SRF and Eppley pyrheliometer calibrations is about 0.5 percent with the SRF factors higher. This means that on the average the SRF calibrations will give lower irradiance values.

Solar Source - Pyranometers

Calibration is transferred from a pyrheliometer to a pyranometer by the shade method. In this procedure, separate measurements are made of the global (direct plus diffuse) and the diffuse irradiance with the pyranometer. The difference of these two measurements is the vertical component of the direct radiation. This difference is compared with a simultaneous measurement of the direct irradiance made with a pyrheliometer to derive the pyranometer calibration factor. In practice, these calibrations are made over a large range of solar zenith angles to obtain an emipirical measure of the instrument's cosine response.

Shade calibration was performed only for the reference pyranometers. Other pyranometers are calibrated by direct comparison in sunlight with the reference pyranometer. The method of calibration involves the calculation of a linear (least squares) regression equation from ten-minute average values of the outputs of the test and reference instruments. The calibration value for the test instrument is obtained by substituting the calibration value for the reference instrument into this equation:

$$C(\text{test}) = a + b\, C(\text{ref}) ,$$

where C is the calibration value, and a and b are the intercept and slope from the regression calculation. The final calibration value for the pyranometer is the average of from 10 to 15 daily values. The daily calibration period is the entire sunlight period, and all days except for those with snow, rain, or low overcast cloudiness are used.

During the period from June to August of 1978, 436 shade calibrations were performed on 6 different Eppley PSP and Spectrolab pyranometers in an effort to obtain better reference pyranometers. Earlier tests had shown that the two reference pyranometers carried over from the NOAA/NWS calibration effort, Eppley PSP 9012 and Spectrolab 73-1, were not suitable for use as reference instruments in outdoor calibrations. Figure B1 is a plot of the calibration data for Eppley 14861 from shade tests made in August 1978 with the TMI absolute radiometer as the standard. In the figure, the derived calibration values are plotted as a function of the sun's elevation angle. The different symbols represent four different days. In the lower right-hand corner of the figure the data have been replotted to give an empirical cosine response curve. The previously accepted calibration value for PSP 14861 was 9.05 based on extended direct comparisons with the SRF reference pyranometer PSP 14886. In Figure B1, the accepted value intersects the calibration curve at a sun elevation near 60°. The shade calibrations of the other 5 pyranometers gave similar results, namely, that the previously accepted value applied to a sun elevation of about 60°. The previously accepted values for each of these instruments was obtained from the reference pyranometer PSP 14886, which in turn was calibrated by extensive comparisons with the carryover NOAA/NWS reference pyranometers Eppley PSP 9012 and Spectrolab 73-1. Thus, the calibration level for pyranometers of the SRF is with reference to a sun elevation of 60°.

One hundred twenty-four pyranometers from outside sources were calibrated by the SRF during 1978. This does not include those pyranometers calibrated for/after use in the NOAA network.

A ratio method has been introduced for the calibration of Eppley model 8-48 pyranometers because of the opposite shape of their respective cosine response curves at low sun angles. This method uses the sums for the day of the 10-minute average millivolt values from the test and reference instruments to give the daily calibration value. The daily values for the test period are averaged to give a single value which is then adjusted to the "September level". The adjustment factor is based on the ratio of the derived calibration factor for the

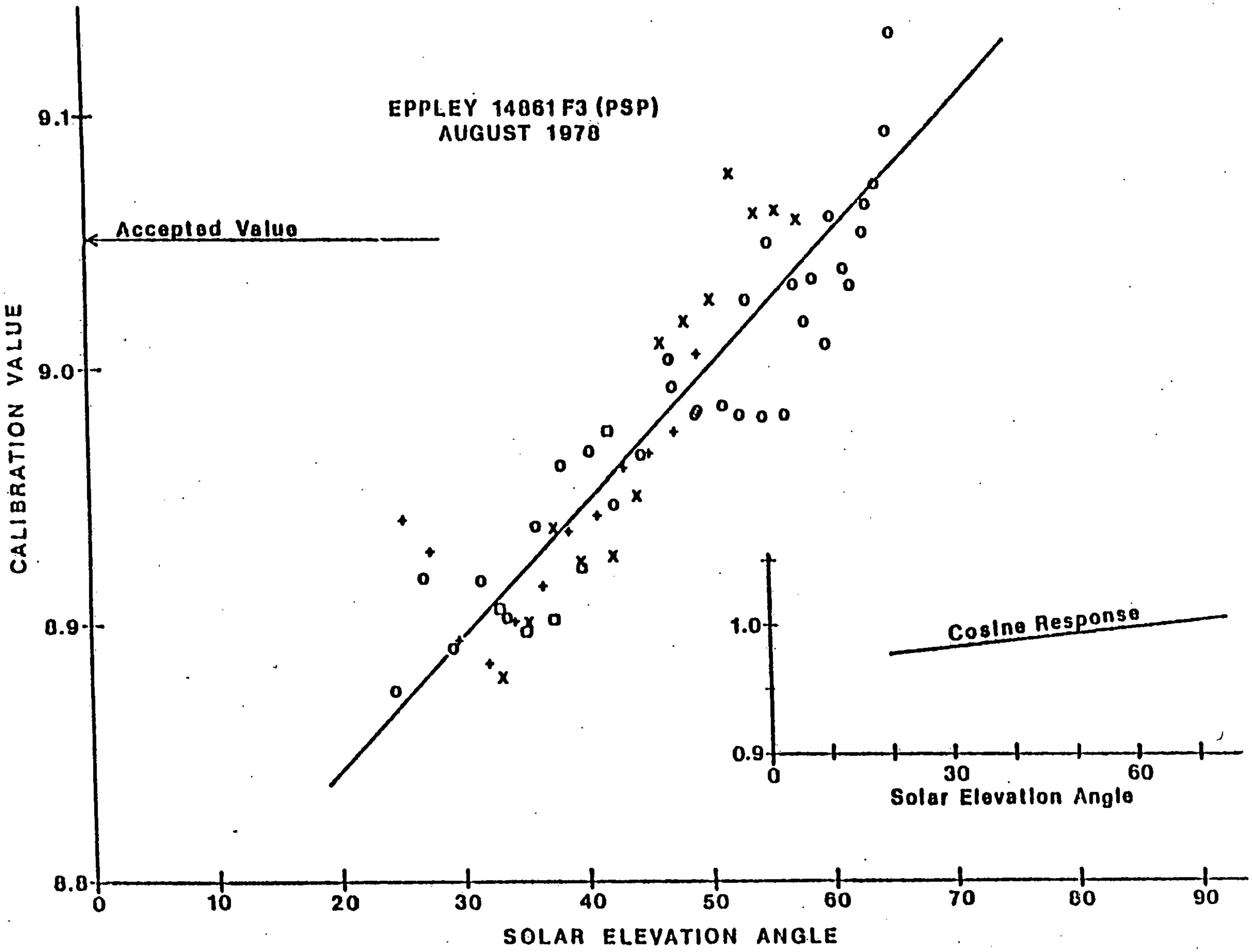

Figure B1. Results of sun and shade calibration of reference pyranometer.

same time period for two SRF Model 8-48 pyranometers to the assigned calibration values for these same instruments. The assigned values were those obtained during the month of September. The September level normalization has also been used for most of the other SRF instruments.

The regression and ratio methods give calibration values for Eppley PSP and Spectrolab pyranometers that agree within a few tenths of a percent. The regression method will be retained for these instruments since it allows for a wider range of objective methods for editing the input data. The regression method is essentially a calibration at 1000 w/m^2 whereas the ratio method is dependent on the daily total radiation power.

Table 3 presents a comparison of SRF and Eppley Laboratory calibrations of 67 Eppley PSP instruments during 1978. All instruments were

Table 3

Comparison of SRF and Eppley Pyranometer Calibration Factors-Frequency Distribution of Ratio C_{SRF}/C_{EPLAB}*

Ratio C_{SRF}/C_{EPLAB}	Number of Instruments
≤0.949	1
0.950-0.959	2
0.960-0.969	2
0.970-0.979	10
0.980-0.989	25
0.990-0.999	20
1.000-1.009	5
1.010-1.019	0
1.020-1.029	2
≥1.030	0

*These data are presented here because they illustrate well the accuracies which can be expected from the best calibrations. Both the SRF and Eppley Laboratories are judged to be using good procedures and both are judged to be careful in their work. These data do not illustrate the correctness of procedures at either facility. These instruments are the best available.

calibrated on the absolute radiation scale by both laboratories. The median level here is about 0.985 although 30 percent of the instruments were in the next higher interval, 0.990 to 0.999. The ratios are the SRF calibration factor divided by the Eppley factor so that the median level of 0.985 means the SRF calibrations will produce irradiance values about 1.5 percent higher than the Eppley factors. If the SRF calibration level represents a sun angle near 60°, as indicated in the previous section, then the Eppley level presumably is for an even higher solar elevation.

The difference described here between Eppley and the SRF for both pyranometers and pyrheliometers are more likely to be real calibration differences at the time of calibration rather than changes in sensitivity of the instruments since the instruments included in the tables were all of recent manufacture.

During 1978, most of the Spectrolab pyranometers used in the NOAA network during 1977 have been recalibrated. Only Spectrolab pyranometers were used in the network in 1977. Although replacement instruments were sent to all stations, several of them have not yet made the change. Table 4 presents the recalibration results. The recalibration values are based on from several weeks to several months of comparison; the original calibrations were based on several clear days over a two week period during November-December 1976. Changes of as much as 2 percent are probably within the range of testing errors, mostly in the original calibrations. Differences larger than this are probably real changes in sensitivity. Since 1977 was the first extended outdoor exposure of these instruments, more time is needed to determine whether real changes in sensitivity have occurred. The very large change in instrument 73-48 used at Fairbanks is not explainable at this time. Both the original and recalibration data have been reviewed and are correct.

Laboratory Temperature Tests

Temperature tests were carried out in a chamber over the temperature range from +40 to -49°C. The light source, a 500 W General

Table 4

Recalibration of Spectrolab Pyranometers

LOCATION	USE	SERIAL NR	CALIBRATIONS 1976	1978	%CHANGE	
Albuquerque, NM	Global	73-46	8.11	8.19	+0.9	
	Diffuse	73-18	8.14	8.22	+1.0	
Bismarck, ND	Global	73-87	10.07	9.92	-1.5	
	Diffuse	73-65	10.07	10.07	0	
Blue Hill, MA	Global	73-82	8.78			
	Diffuse	73-88	8.80			
Boise, ID	Global	73-90	9.33	9.29	-0.4	
Boulder, CO	Global	73-50	9.72	9.35	-3.8	
	Diffuse	73-89	8.75			
Brownsville, TX	Global	73-21	8.57	8.51	-0.7	
	Diffuse	73-47	8.59	8.57	-0.2	
Burlington, VT	Global	73-70	12.17	12.22	+0.4	
Caribou, ME	Global	73-101	10.52	10.37	-1.5	
Columbia, MO	Global	73-44	8.89	8.80	-1.0	
Dodge City, KS	Global	73-43	9.25	9.32	+0.8	
El Paso, TX	Global	73-54	8.06	8.19	+1.9	
Ely, NV	Global	73-83	8.47	8.33	-1.7	
	Diffuse	73-100	8.48	8.30	-2.1	
Fairbanks, AK	Global	73-48	10.63	8.61	-23.5	
Fresno, CA	Global	73-80	8.58	8.46	-1.4	
Grand Junction, CO	Global	73-84	8.24	8.16	-1.0	
Great Falls, MT	Global	73-68	10.46	10.04	-4.2	
Indianapolis, IN	Global	73-34	9.54			
Lake Charles, LA	Global	73-55	8.50	8.26	-2.8	
Lander, WY	Global	73-61	8.34	8.47	+1.5	
Las Vegas, NV	Global	73-92	8.41	8.28	-1.5	
Los Angeles, CA	Global	73-66	9.89	9.80	-0.9	(Not used)
	Diffuse	73-99	9.88	9.79	-0.9	(Not used)
Madison, WI	Global	73-69	9.99	9.79	-2.0	
Medford, OR	Global	73-38	9.91	10.09	+1.8	
Miami, FL	Global	73-56	8.71	8.72	+0.1	
Midland, TX	Global	73-59	7.99	8.01	+0.2	
Montgomery, AL	Global	73-40	8.84	8.74	-1.2	
Nashville, TN	Global	73-23	9.47	9.58	+1.2	
Omaha, NE	Global	73-63	8.38	8.40	+0.3	
Phoenix, AZ	Global	73-67	8.80	8.82	+0.2	
Pittsburgh, PA	Global	73-19	8.43	8.62	+2.2	
Raleigh, NC	Global	73-31	9.06	8.81	-2.8	
Salt Lake City, UT	Global	73-97	8.71			
Seattle, WA	Global	73-62	9.50	9.78	+3.0	
	Diffuse	73-98	9.49	9.35	-1.5	
Sterling, VA	Global	73-60	8.67			
	Diffuse	73-93	8.68			
Tallahassee, FL	Global	73-41	8.97	8.75	-2.5	
	Diffuse	73-37	8.95	8.75	-2.2	

Electric (GE) "Quartzline" (Q500 PAR 56/MFL) flood lamp, was located outside the chamber and illuminated the sensor through a window in the top of the chamber. A photocell was mounted outside the window to monitor the output of the lamp. The lamp current, chamber temperature, sensor temperature, photocell output and sensor output were measured continuously. Tests were performed using various cooling and heating cycles in order to arrive at a procedure which produced results which could be repeated.

Tilt Tests

Ten different pyranometers from eight manufacturers were tested in the laboratory to determine changes in sensititivity caused by operating the instrument at angles tilted from the horizontal. Figure B2 is a schematic view of the tilt box used for the experiment. The light source, a 650 w quartz halogen lamp, was located in the center of the box and illuminated two identical chambers on each end which contained the pyranometers. The light source was on the center of rotation and rotated with the box that it always had the same relationship to the pyranometers. Opal glass windows separated the lamp chamber from the pyranometer chambers. All of the chambers were ventilated with fans.

Lamp voltage was controlled by a regulator and monitored with a digital multimeter. Control was achieved to ±0.03 volts at a nominal voltage of 115 v. Pyranometer outputs were monitored with a data logger whose accuracy was ±1 microvolt. Pyranometer outputs ranged between 0.8 and 10 millivolts with a typical irradiance of 450 w/m^2. Tests of the variability of lamp output with voltage showed that the observed lamp voltage variations accounted for less than 0.05 percent change in pyranometer output and were insignificant.

For the experiments, pyranometers were placed in each chamber, one chamber serving as a control always contained the same pyranometer. Two procedures were used. In the first, the box was rotated through successively greater tilt angles, each angle separated by exposure at 0° tilt (e.g., 0°, 10°, 0°, 20°, 0°, 30°, etc.). In the second, the

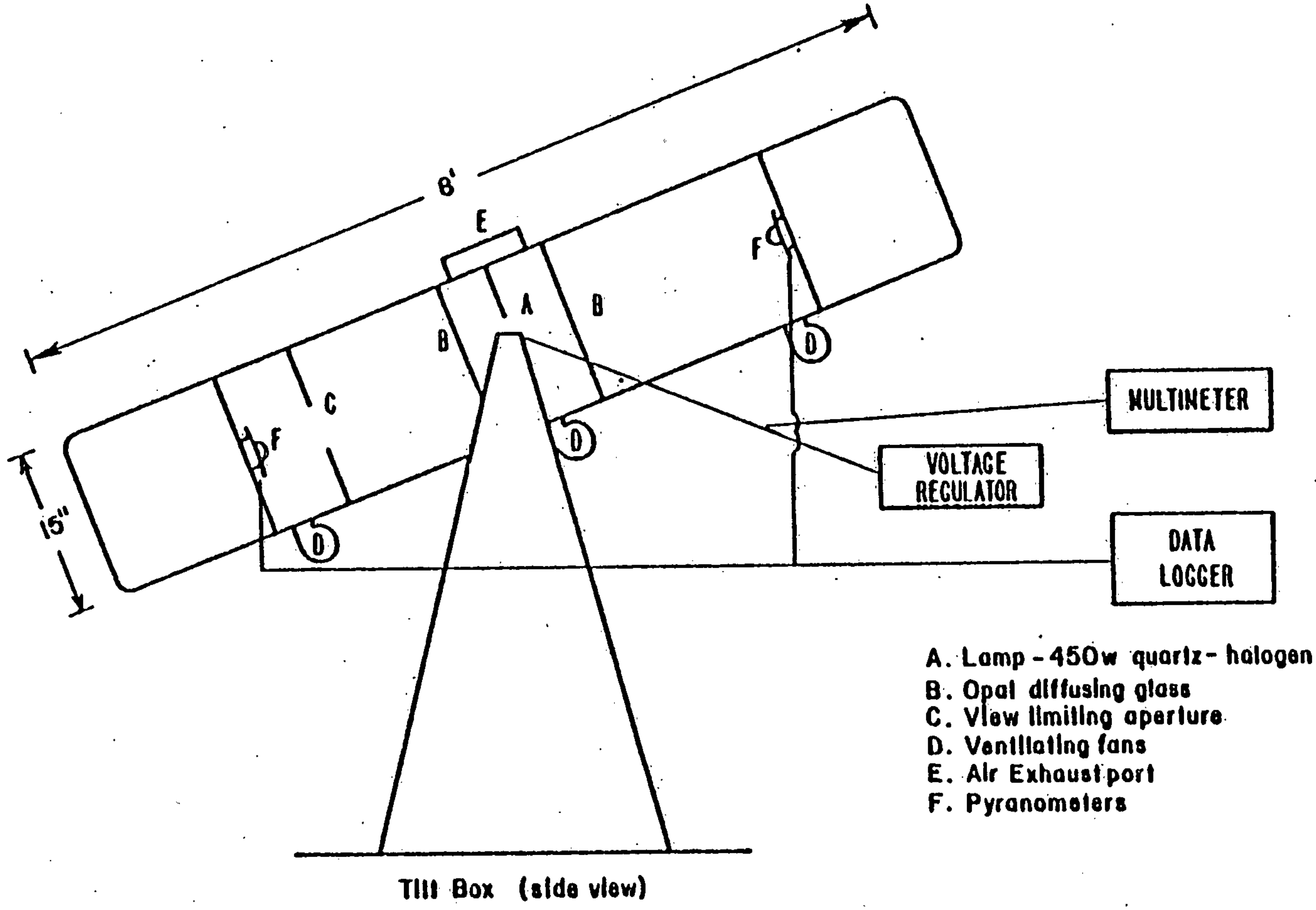

Figure B2. Tilt box for testing effects of tilting pyranometers. (Courtesy of NOAA SRF, Boulder.)

same tilt angle was repeated two or three times before moving to a larger tilt angle (e.g., 0°, 10°, 0°, 10°, 0°, 20°, 0°, 20°, etc.). No differences could be detected in the two procedures. After tests showed that the silicon cell pyranometers were not affected by tilt, one of these was usually included in the array as additional control.

Outdoor Comparisons

One of each kind of pyranometer was exposed outdoors beginning April 1, 1977. Since most pyranometers are used outdoors, the ultimate test is the degree of comparability under continuous exposure in all kinds of weather. The instruments are exposed on the seventh floor penthouse roof of the facility in Boulder. The raw millivolt outputs of the instruments are read onto magnetic tape through a Monitor Labs 9400 data logger. Instantaneous measurements are made once per minute and the basic period of analysis is the ten-minute average. All of the instruments in the array are compared with a reference pyranometer several other pyranometers are always included in the array as additional controls. Figure B3 is excerpted from the computer printout of the analyzed data logger tape. Each line represents one scan of the data logger beginning on the minute indicated on the left. The values are the millivolt outputs of the pyranometers listed at the top of the figure. The instruments are identified as either test or reference instruments. The output from the reference instrument (EP9012) is brought in every sixth or seventh channel, and a reference value for each test instrument is obtained by interpolation between successive reference measurements. For each test instrument a regression equation is calculated from the ten-minute data for the entire daylight period. The bottom line of Figure B3 gives the results for the day; regression equation slope, intercept, standard error and a derived calibration value obtained by inserting the known calibration value for the reference instrument into the regression equation.

Outdoor tilt tests are also done.

CHANNEL	30	31	32	33	34	35	36	37
INSTR ID	EP9012	EP14886	EP12687-Q	EP1881 PBK	EP 2663 LB	EP 12257	EP 9012	EP11935
INSTR TYPE	REF	TEST	TEST	TEST	TEST	TEST	REF	TEST
77272 1000	3.449	6.391	6.025	2.349	2.592	6.161	3.360	6.206
77272 1001	3.454	6.429	6.101	2.361	2.612	6.352	3.478	6.407
77272 1002	3.528	6.547	6.191	2.394	2.647	6.427	3.531	6.511
77272 1003	3.554	6.585	6.221	2.411	2.661	6.456	3.549	6.545
77272 1004	3.452	6.375	5.957	2.359	2.589	6.132	3.390	6.272
77272 1005	3.578	6.632	6.267	2.425	2.676	6.506	3.560	6.597
77272 1006	3.596	6.667	6.300	2.438	2.687	6.542	3.598	6.634
77272 1007	3.614	6.698	6.329	2.455	2.704	6.571	3.615	6.664
77272 1008	3.611	6.682	6.301	2.438	2.683	6.506	3.597	6.644
77272 1009	3.669	6.802	6.432	2.493	2.739	6.679	3.674	6.771
REF AVG	3.551	3.548	3.546	3.544	3.542	3.539	3.537	3.542
TEST AVG		6.580	6.212	2.412	2.659	6.433		6.525
STD DEV.	.078	.145	.147	.047	.049	.174	.100	.180
K*		6.787	6.412	2.491	2.748	6.652		6.743
IRRADIANCE	.970						.966	

CALIBRATIONS:

INTERCEPT		-.01934	-.03275	-.00541	.01201	-.02923		-.03066
SLOPE		1.85988	1.76558	.68210	.73262	1.82462		1.84742
STD ERROR		.02095	.05341	.01093	.03263	.03977		.01700
CAL VALUES		6.78783	6.42929	2.49107	2.69340	6.64888		6.73091

Figure B3. Sample of data analysis for pyranometer calibration.

The Canadian National Atmospheric Radiation Center

J. Ronald Latimer, Downsview, Ontario

General Description of Facility Procedures

A. Purpose

The National Atmospheric Radiation Center of the Canadian (NARC) Atmospheric Environment Service is a Canadian government organization charged with the management of solar and environmental data collection and publication for Canada. This includes the calibration of the solar sensors used.

B. General Tasks

General management of the radiation monitoring network, data collection and publication, instrument calibration,

Standards Maintained

	Manufacturer and Models	Serial No.
A. Absolute Insts.		
1. Eppley-Kendel	1. H-F	1. 11399
B. Pyrhelicmeter		
1. Eppley NIP	1.	1. 4538A
2. Eppley NIP	2.	2. 7217A
3. Eppley NIP	3.	3. 4450A
4. Eppley NIP	4.	4. 7671A
5. Angstrom	5.	5. A9001
C. Pyranometer		
1. Talbert	1. Abbot Pyranometer	1. T1 and T5
2. Eppley PSP	2.	2. 10037
3. Eppley PSP	3.	3. 11671
4. Kipp	4. CM6	4. 69-0309
5. Kipp	5. CM6	5. 71-0980
6. Kipp	6. CM6	6. 71-1109

Instruments Normally Calibrated

Pyrheliometer (no filter)

1. Eppley NIP

Pyranometer (no filter)

1. Eppley PSP
2. Kipp and Zonen
3. Net radiometers

Calibration Methods:

The Canadian National Atmospheric Radiation Center
Downsview, Ontario

Standard Instruments:

The primary standard at the NARC is an absolute instrument. This instrument is normally intercompared with similar instruments during international intercomparisons. It participated in a November 1978 intercomparison, and a May 1979 intercomparison at the Desert Sunshine Exposure Testing Facility at New River, Arizona. This instrument is currently used as the primary standard.

Previously an Angstrom Compensation Pyrheliometer was used. The latter instrument participated in the Fourth International Pyrheliometer Comparison at Davos, Switzerland in 1975.

Working standard pyrheliometers and pyranometers are calibrated by comparison with the primary standard. These processes are illustrated in Figures B4 and B5. These calibrations are done only under the best possible sky conditions at a special high elevation calibration laboratory located in an arid area having only 8 to 9 inches of precipitation annually. This laboratory site was selected for its stable and clear sky. These calibrations are done annually in late June or early July. All pyrheliometer calibrations are done in sunlight and only on the clearest days.

The temperature characteristics of all instruments are determined in the laboratory, and corresponding factors are applied to all data.

Pyranometers are compared in sunlight when the weather permits. An integrating sphere is available for laboratory intercomparison of pyranometers, and this is used to compare instruments of like manufacturers with working standards.

Net pyrradiometers are deployed at 24 stations in Canada. These instruments are calibrated in the laboratory in two different specially designed test chambers which simulate different combinations of blackbody radiation and shortwave radiation.

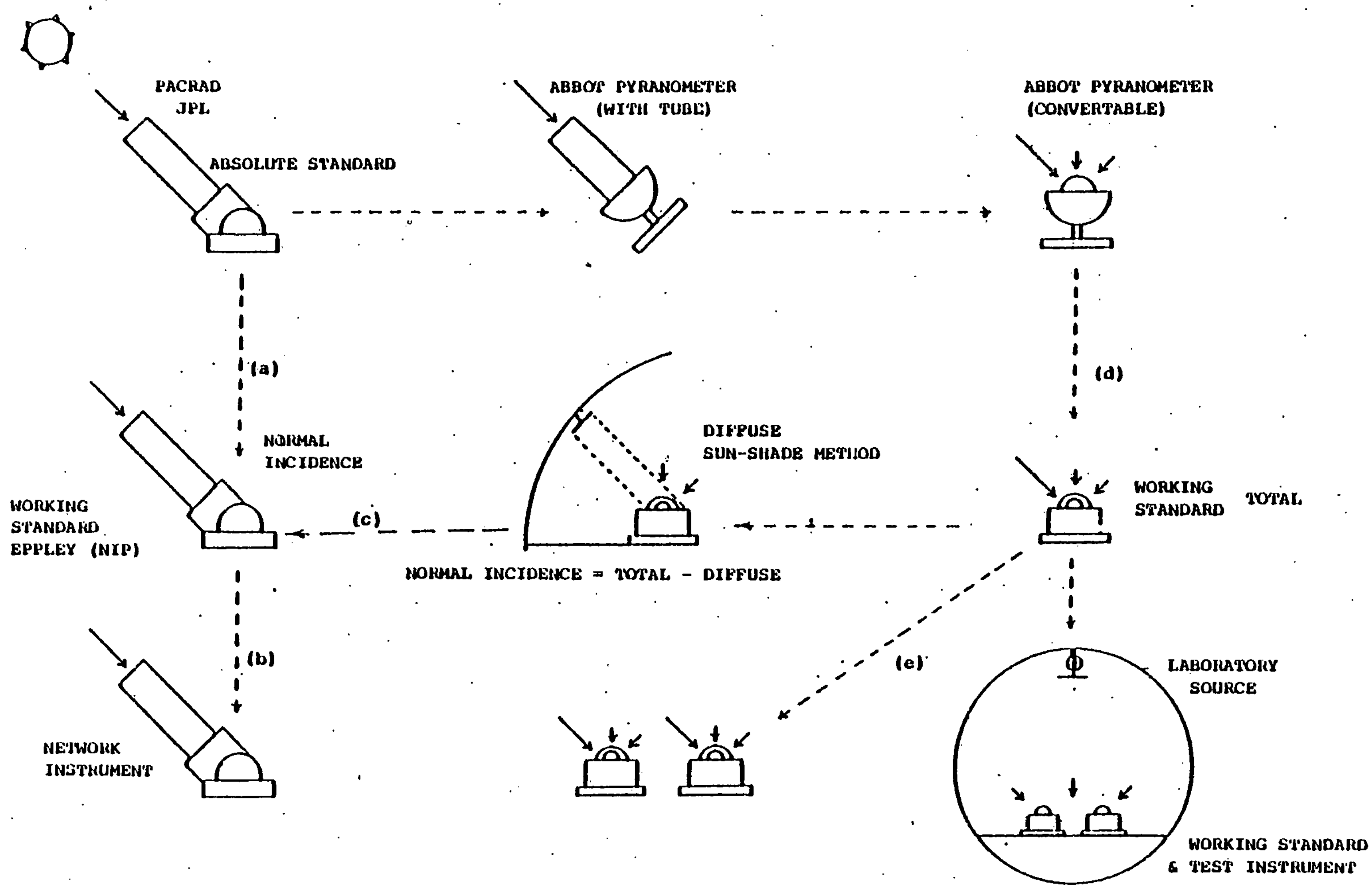

Figure B4. Calibration procedures at the National Atmospheric Radiation Centre, Toronto.

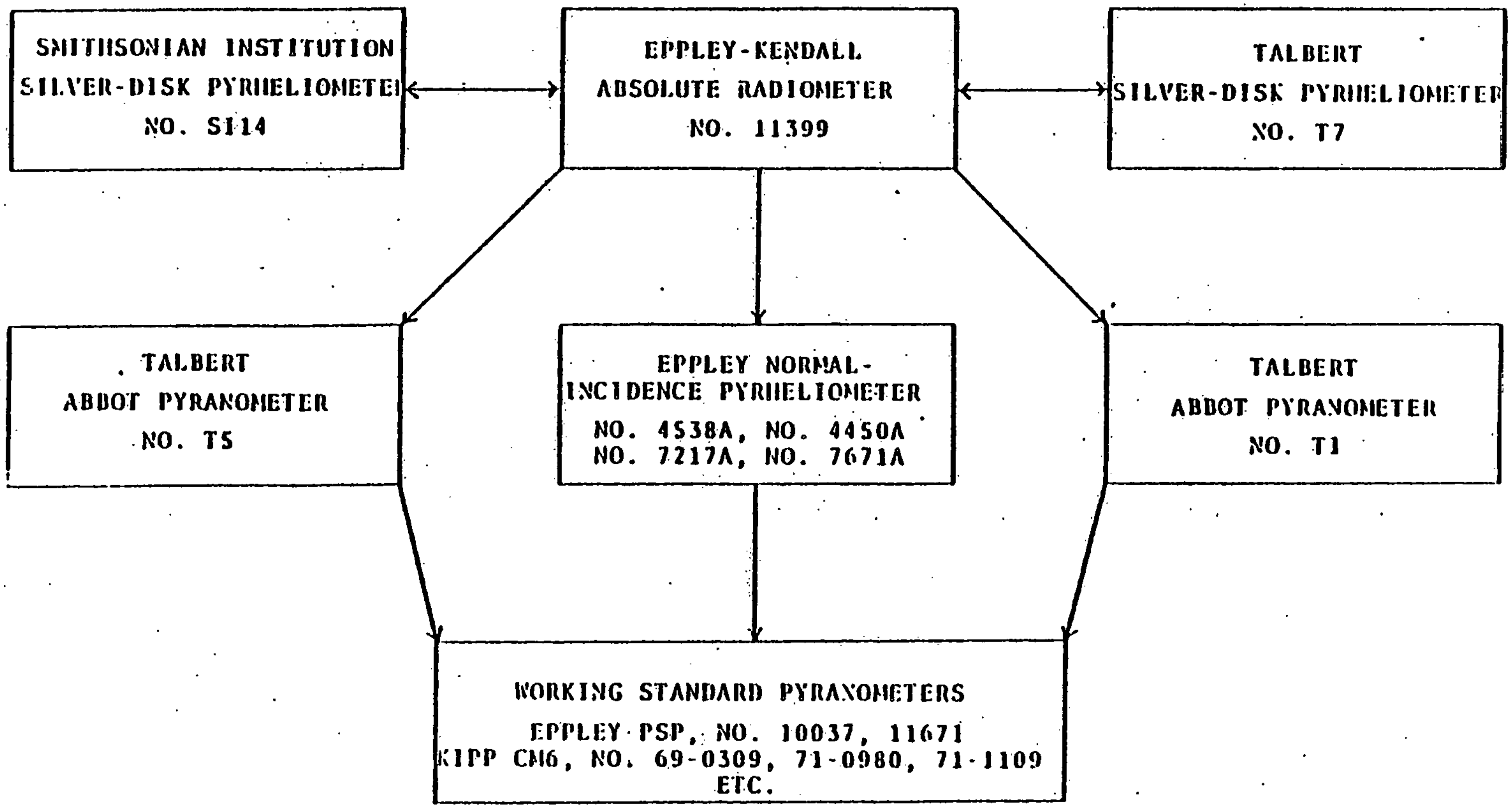

Figure B5. National Atmospheric Radiation Center reference radiometers.

The remainder of this description of the NARC is excerpted from Radiation Measurement, Technical Manual Series No. 2, International Field Year for the Great Lakes, by J. Ronald Latimer.*

SOLAR SOURCE - PYRHELIOMETERS

By Reference to a Working Standard Pyrheliometer

The first of these methods entails simultaneous exposure, outdoors, of the pyranometer under test and a standard pyrheliometer directed at the sun. In principle, a comparison is made between the computed vertical component of the solar intensity as measured by a pyrheliometer with that measured by the radiometer. Occasions should be selected with clear skies and steady radiation (as judged from the record). The direct component is eliminated temporarily from the horizontal surface radiometer (pyranometer, pyrradiometer, etc.) by shading the whole outer envelope of the instrument with a disk of sufficient size mounted on a slender rod and held some distance away. For most purposes, the disk should be 100 mm in diameter when held a distance of 1 m from the radiometer receiver. In this way, the angle subtended at the latter will closely approximate that of the aperture of the reference pyrheliometer (about 6°). This arrangement occludes both the direct solar beam and the circumsolar sky radiation, both of which fall on the pyrheliometer sensing element. The period required for occulting depends on the response time of the radiometer and the steadiness of the radiation flux, but ten minutes should generally be sufficient.

Subtraction of the value averaged over the shading interval from the corresponding value averaged over the exposed interval yields S, the vertical component of direct solar radiation measured by the radiometer. Thus:

$I \sin h = S/k$,
or $k = S/(I \sin h)$,
where I is the solar intensity,
h is the solar elevation,
and k is the calibration factor.

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The solar elevation should be measured during the shading operation or computed (to the nearest 0.1°) for this period from the time. If I is measured in W m^{-2} and S is derived in millivolts, then the calibration factor k is obtained in millivolts/W m^{-2}. The mean instrument temperature should always be noted.

In order to compute sin h, it is necessary to know the geographical latitute ϕ, the date (from which to obtain the solar declination, δ) and the time of observation (IGY, 1958). Then make use of the expression

$$\sin h = \sin \phi \sin \delta + \cos \phi \cos \delta \cos t$$

where t is the hour angle of the sun. (24 hours = 360°; solar noon is 0° and hence, cos t at true solar noon is unity.)

Consider the following example. The place is Toronto at latitude 43° 42', longitude 79° 14' W and the date/time is September 6 at 11:43 Eastern Standard Time (EST). The Local Apparent Time equivalent to 11:43 EST is 11:28 and t = 32 x 15/60 = 8.00°. The solar declination δ may be found for each day in a current Nautical Almanac. Hence

$$\phi = 43.70°,\ \delta = 6.78°,\ t = 8.00° \text{ and}$$
$$\sin h = \sin 43.70° \sin 6.78° + \cos 43.70° \cos 6.78° \cos 8.00°$$
$$= (0.6909 \times 0.1181) + (0.7230 \times 0.9931 \times 0.9903)$$
$$= .0816 + .7110 = 0.7926.$$

It is difficult to recommend a specific number of such determinations on which to base the required value of the radiometer factor. The principal variations (apart from fluctuations due to atmospheric conditions and observing limitations) are due to:

1. departures from cosine law response, particularly at solar elevations less than 10°,
2. the ambient temperature,
3. imperfect leveling of the receiver surface.

<u>By Comparison with a Reference Radiometer</u>

Comparison entails the simultaneous operation of two horizontal surface radiometers of the same type side by side outdoors for a sufficiently long period to acquire representative comparisons. This may take several weeks if weather conditions are unfavorable. The derivation of the instrument factor is straightforward. A selection should be made from the two sets of records of occasions when the traces are sufficiently high and reasonably smooth. Each mean value of the ratio R of the response of the test to the reference instrument may be used to calculate $k_u = R.k_s$, where k_s is the calibration factor of the standard and k_u is the calibration factor being derived.

A variation of the shading or occulting method may also be used which involves occulting one or more pyranometers or pyrradiometers simultaneously with a reference pyranometer or pyrradiometer. Subtraction of the values averaged over the shading interval from the corresponding average taken over the exposed interval yields the vertical component of direct solar radiation S measured by each instrument. If S is derived in millivolts, then the calibration factor $k_u = k_s \cdot S_u/S_s$, in mV W m^{-2}, is obtained.

The mean temperature of the instruments should be recorded during all outdoor calibration work.

<u>Laboratory Quartz Envelope Tungsten-Filament Source</u>

There are two methods which involve laboratory-maintained artificial lamp sources replacing the sun. Here, a distinction is made between direct and diffuse radiation. In one instance, exposure is to a regulated tungsten-filament lamp installed at the end of an optical bench (Drummond, 1969). A practical source for this type of work is a 5 kW lamp mounted in a forced-ventilated water-cooled housing with the emission limited to the solar spectrum by a quartz window. When calibrating pyranometers and pyrradiometers in this way, special care is necessary to exclude reflection effects from the comparisons by using black screens. In the case of pyrradiometers, special precautions must be taken to provide constant temperature surroundings during the comparison. The usual procedure is first to install the reference instrument and measure the radiant flux. The reference is then removed and the measurement repeated with the test instrument. The reference is then replaced and another determination made. The repeated alternation with the reference should produce a set of measurement data of good precision ($\sim$0.5%). The mean ratio of the response R of the unknown to the standard may then be used to calculate $k_u = R.k_s$.

There is no question that the best method for the indoors' calibration of pyranometers entails the use of an integrating light system, such as a sphere or hemisphere illuminated by tungsten lamps, with the inner surface coated with highly reflective diffuse-white paint (Hill, 1966; Latimer, 1966; Drummond and Greer, 1966). The advantage of this controlled system is that the reference and test instruments are exposed at a fairly constant temperature without being subject to the effects of varying solar elevation and azimuth, and atmospheric pollution.

It must be stressed that when an artificial source is employed as a substitute for the sun, there is a need to compare like instruments at all times. The reference and test instruments should always be of the same construction and have the same spectral response. The precision of integrating sphere measurement is generally within ±0.5%.

Blackbody Source

This is the most difficult of the procedures and must be carried out on all instruments measuring long-wave radiation. The radiometer is alternately exposed to a hot blackbody and then to a cooler one (usually called the shutter), and the sensor signal recorded (Drummond, 1969). When the sensor views the blackbody, and when interreflections between it and the blackbody are insignificant, the net radiant flux density W_1 absorbed by the sensor is given by:

$$W_1 = \sigma \varepsilon_0 \varepsilon_1 F_{01} (T^4{}_1 - T^4{}_{01}) + R$$

where

ε_0 = emissivity of the sensor,

ε_1 = emissivity of the blackbody,

F_{01} = a nondimensional geometrical factor,

T_1 = temperature of the blackbody,

T_{01} = temperature of the sensor surface when exposed to the blackbody,

R = net radiant flux due to the surroundings.

When the sensor views the shutter, then:

$$W_2 = \sigma\varepsilon_0\varepsilon_2F_{02}(T_2^4 - T_{02}^4) + R$$

where

ε_2 = emissivity of the shutter,

T_2 = temperature of the shutter,

T_{02} = temperature of the sensor surface when exposed to the shutter.

Care should be exercised to ensure that the quantity R is the same in both cases. It depends upon, for example, proper location of the shutter. The sensor is usually mounted in an isothermal enclosure with nonreflecting walls. Making $F_{01} = F_{02}$ and subtracting the equations yields

$$W_1 - W_2 = \sigma\varepsilon_0F_{01}[\varepsilon_1(T_1^4 - T_{01}^4) - \varepsilon_2(T_2^4 - T_{02}^4)]$$

which is the absolute net flux at the detector surface due to the blackbodies at known temperatures, thus allowing an absolute calibration of the detector.

This equation is frequently written in a simpler form:

$$W_1 - W_2 = \sigma\varepsilon_0\varepsilon_1F_{01}(T_1^4 - T_2^4)$$

If T_1 is sufficiently high, this approximation is valid. Ideally, $T_2 = T_{02}$ and the second term on the right side vanishes.

Routine Checks on Calibration Factors

There are several possible methods of checking the constancy of the calibration of radiometers depending upon the equipment available at a particular station. It cannot be stressed too strongly that no opportunity to check the performance of radiometers in the field should be missed.

SOLAR SOURCE - PYRANOMETER COSINE RESPONSE

The dependencies of the directional response of the receiver upon solar elevation and azimuth are usually known as the Lambert cosine response and the azimuth response, respectively. Ideally, the sensor of the receiver is proportional to the cosine of the zenith angle of the solar beam and is constant at all azimuth angles. For pyranometers, it is convenient to assess the error in percent when the sun is at an elevation of 10° on a clear day. Integral errors caused by departure from the required cosine and azimuth responses of the sensor should not exceed ±5 to 7% for pyranometers and ±10% for pyrradiometers.

Measurement of cosine and azimuth responses can also be carried out in the laboratory. The equipment used for this test comprises an optical bench, a stable lamp source with collimated beam and an instrument turntable graduated in degrees. The lamp is supplied from a voltage stabilized source (rated ±0.1%) to ensure constant output. The response of the radiometer is recorded as the angle of incidence of the radiation is varied through a series of fixed azimuth and elevation angles. Care should be exercised to ensure that there is no significant influence due to scattered radiation. Figure B6 shows the typical response of a Kipp and Zonen pyranometer, and Eppley (180° pyrheliometer), black and white, and precision spectral pyranometers. Average values were taken for different azimuth positions. The Kipp and Eppley 180° and Model 15 pyranometers were examined at the National Atmospheric Radiation Center (NARC), and the Eppley black and white and Model 2 at the Eppley Laboratory. At the Eppley Laboratory, it is customary to express the percent deviation with respect to the 45° incidence value. The ratio R (in percent) is given by:

$$R = 100\ V_\Theta/(V_0 . \cos\Theta)$$

where

V_Θ = response at Θ°,

V_0 = response at nominal incidence,

Θ = angle of incidence

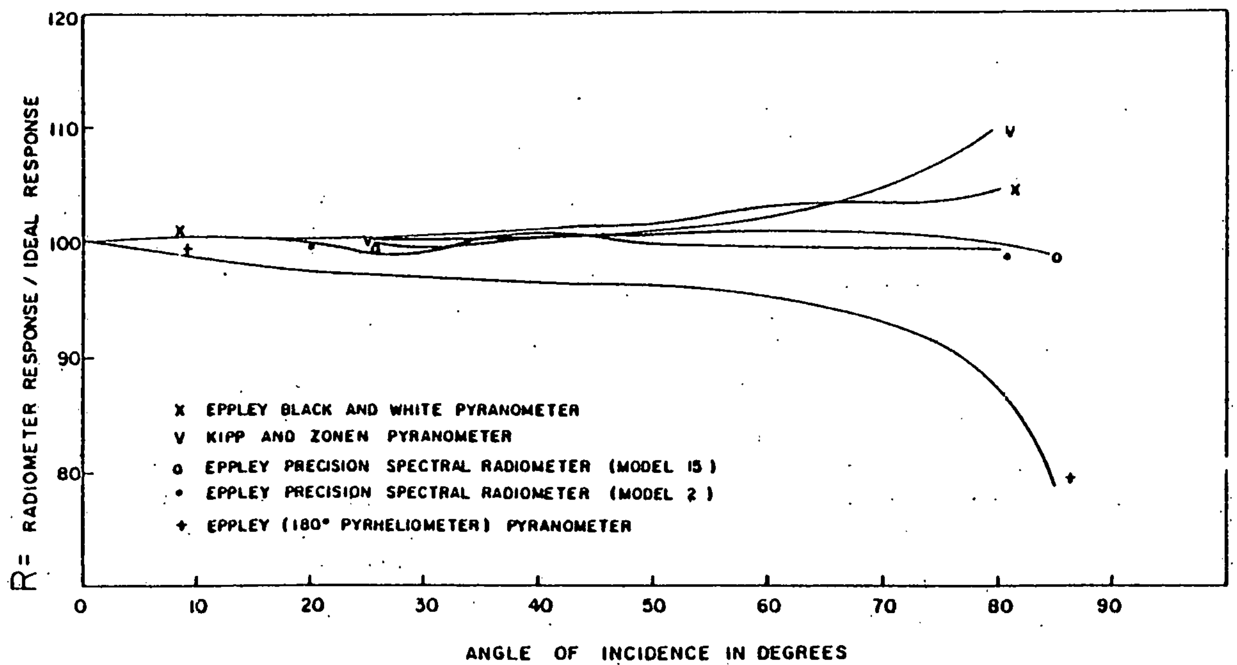

Figure B6. Typical cosine response of a number of radiometers.

Stability of the Calibration Factor

The maximum permissible change in the factor is ±2% per year (WMO, 1968). This stability is readily achieved with the instruments mentioned here when they are handled with care. Additional confidence can be assured by frequent checking of the calibration in the field when this is practical.

Change of Response Due to Variation to Ambient Temperature

Thermopile radiometers exhibit a change in response with variation in instrument temperature. Some instruments are equipped with built-in temperature compensation circuits in an effort to maintain a constant response over a large range of temperatures. The temperature variation of response of radiometers may be measured in a temperature-controlled chamber. The temperature in the chamber is varied over a suitable range (-40° to +40°C) in ten degree steps and held steady at each step until the response of the radiometer has stabilized. The data are then plotted and a smooth curve drawn through the points. If the radiometer has a built-in temperature compensation circuit, the plotted data should be examined to ascertain whether the radiometer response remains within the specified limits over the range. If the instrument has no built-in compensation circuit, a temperature coefficient α may be calculated using the following expression:

$$\alpha = \frac{V_{T2}/V_{T1} - 1}{T_2 - T_1}$$

where

V_{T2} = response in mV at temperature T_2,

V_{T1} = response in mV at temperature T_1.

The computation is based on use of the best straight-line fit of the data over the temperature range of interest.

Variations in Spectral Response

Errors caused by a departure from the required spectral response of the sensor should not exceed ±2% over the range of interest (WMO, 1968). Instruments with thermopiles coated with Parsons' black or 3M Velvet

Black 101C10, with selected optical grade hemispheres, usually present no problem in this respect. Photodetectors have a very large variation of spectral response and have not been used successfully to measure radiant flux over a large spectral range.

Nonlinearity of Response

The response of radiometers should be within ±2% of being linear (WMO, 1968). Specimens in good condition of the models treated here are known to meet this requirement over the range of radiant intensities generally encountered (i.e. up to 1.4 kW m^{-2}).

Time Response of Radiometers

The speed of response is simply measured in the following manner. A radiometer is irradiated through an aperture and shutter, and its output registered by means of a fast response recorder (an oscilloscope) as the shutter is alternately opened and closed. Care must be taken that the effect of the surrounding does not change during the experiment. The recording shows response versus time for a step-function increase and decrease to a new constant level of radiant energy. Radiation sensors should have first order response, nonoscillatory or critically damped characteristics. In such cases, the response time is called the time constant and corresponds to the elapsed time required for the signal to be reduced to 1/e or 36.8% of its initial value.

The time constant of radiometers should be less than 60 s since, as a rule, it is necessary to wait up to four times this value to obtain a steady rating, which is an important feature during calibration (WMO, 1968). It is also important when it comes to the selection of recording-integrating systems.

References

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Utah State University
College of Agriculture
Department of Soil Science and Biometerology
Logan, Utah

A variety of pyranometer calibration tests have been performed at Utah State University in support of a program to measure the distribution of solar availability across the Rocky Mountains along a line at approximately 40°N latitude. These procedures have been reported in a recent publication.* Portions of that article applying specifically to calibration are quoted below:

"1. <u>"Flat" (equal) response over the entire spectrum of the solar radiation (0.3 to 3 microns)</u>

One important requirement for correct detection of the heat effect of a radiation source is that the sensor provide nonspecific spectral sensitivity. The black paints used in today's pyranometers are reasonably well tested as to this characteristic and meet the criteria. The pigments of white paints that were used until a few years ago, however, generally showed decreasing reflectivity in the infrared, and thus, if used in pyranometers, led to a diminished sensitivity beyond the longwave end of the visible range. Also, these pigments as well as their binder, reduced the reflectivity in the UV. Therefore, although the amount of energy recorded in these wavelengths is small (usually not more than 2-4%), errors that could influence the results were encountered particularly in the mountains where high UV levels occur.

"The new white paints, which use BaS as pigments and binders on a water base, permit a perfectly flat reflectivity over the entire solar spectrum from 0.3 to 3 microns. Black and white pyranometers can now be considered equivalent to black surface instruments in their spectral response. The most frequently used, spectrally adequate, white paint is produced by Kodak.

"The application requirements to the support demand a layer of paint at least 1 mm in thickness. In pyranometers, such a layer of paint would produce a high heat capacity in

*Mohr, Dahlberg and Dirmhirn, "Experiences with Tests and Calibrations of Pyranometers for a Mesoscale Solar-Irradiance Network," Solar Energy, Vol. 22, No. 3, 1979, pp. 197-203.

Instruments Normally Calibrated

Pyranometer (no filter)

1. Eppley PSP

2. Schenk Star

Standards Maintained

Absolute Insts.	Manufacturer and Models	Serial No.
1. One	1. TMI Mark IV	1. #67707

Pyranometer

1. One	1. Eppley PSP	1. #15693F3

the receiver surface and, consequently, a low response time. Thick layers of paint also break easily during instrument handling. To avoid this disadvantage in the Schenk Black and White Star Pyranometers, the receiver is painted with commercially available paint and coated with a thin layer of Kodak White Paint. We duplicated this procedure on copper plates, and determined their reflectivity on a Beckman DK-2A spectro-reflectometer.

"2. Linearity

Linearity between radiative energy and electrical output is one of the most fundamental requirements for proper irradiance measurements. Deviations from linearity can be caused by improper performance of the pyranometer or the electric recording equipment. Hence, both have to be checked prior to operation.

"The recording device can easily be tested by calibrating using a variable power supply of high (laboratory) accuracy. Recording equipment often were not satisfactory with regard to linearity and had to be adjusted.

"Pyranometers can be tested by mounting a rotating adjustable sector above the pyranometer. The table in our setup was adjustable so the pyranometer sat perpendicular to the sun. The disk could be opened half way and closed fully in increments of one-sixteenth of the surface area of the disk. Two readings were taken while the disk was not rotating: one, when the sun hit the pyranometer; and second, when the shaded portion was over the pyranometer so that only the diffuse radiation was detected. The difference between the global and the diffuse readings gave us the direct irradiance which was used as the 100% value. Next, the rotating disk was turned on while it was in the half closed position and the reading taken when a constant value was reached. Additional readings in increments of sixteenths of the surface area of the disk were taken with a voltmeter at intervals between half to complete obstruction of the sun. (See photograph 1.)

"3. Cosine Response

Laboratory results of cosine response

"Twenty-three star pyranometers and one Eppley precision pyranometer were tested in the optics dark laboratory at Utah State University for proper cosine response. The test equipment consisted of a sliding light source that could be moved along a half circular rod, with the pyranometer mounted in the center. (See photograph 2.)

"A quartz iodine lamp with 5 mm aperture acted as a point source. The light source was set 90 mm away from the pyranometer's active service. A lens was used so the light reaching the pyranometer was essentially parallel.

"Care was taken to provide a homogeneous light front by centering the light source, lens, and aperture in the systems center plane. After this was accomplished, a small silicon cell of 3 mm diameter was used to check the homogeneity of the light front at the location of the pyranometer.

"Readings were taken at incidence angles of 0° (when the light was perpendicular to the pyranometers active surface) 20°, 40°, 50°, 60°, 70°, 75°, 80°, 85°, and 90°. A shading disk was provided in front of the light source so that any stray light could be subtracted. Alternate unobstructed and shaded measurements were taken.

"<u>Field tests of the cosine response</u>

Because of the importance of guaranteeing a proper cosine response of the pyranometers, a second method was applied using the sun as a source. This allowed us to detect any eventual deviations connected with higher levels of radiation.

"An adjustable platform was built for elevation and azimuth adjustments (accuracy of 1° or better). The platform was fixed to a table and leveled with two-dimensional libellas and leveling screws. A diopter, as used in pyrheliometers, was provided for adjusting the table perpendicular to the sun.

"Readings were taken at 0°, (perpendicular to the sun) 20°, 40°, 50°, 60°, 70°, 80°, 85°, and 90°. Since the sun is constantly changing positions, 0°, or perpendicular readings, were taken again after the 0°, 50°, 75°, 90°, readings, and adjustments made as needed.

"Diffuse radiation also changes, but at a much slower rate than global radiation. Diffuse radiation measurements were taken with an obscuring disk at 0°, 50°, 75°, and 90°. Changes in diffuse radiation were graphed with respect to solar angles. Global minus diffuse radiation provided the direct beam which we used to determine the cosine response.

"The zero point on each pyranometer must also be checked. This was achieved by completely covering the pyranometer and determining the adjustment to zero.

"The field tests of the cosine response were then compared to the laboratory results. Only 8 pyranometers, samples from each of the few groupings from the laboratory tests, were investigated outdoors. Reproducibility of the cosine response was very good, with negligible deviations between laboratory and outdoor measurements.

"4. <u>Positional Effects (tilt effect)</u>

Some pyranometers change in sensitivity when tilted or inverted. The behavior of the star pyranometer when tilted had not been previously reported, so we performed suitable laboratory tests.

"A light source and a pyranometer were placed 1 m apart and directly opposite to each other on a rotating boom. The light source consisted of a quartz iodide lamp and a lens system that amplified and provided parallel radiation. The pyranometer was mounted perpendicular to the beam. Such an arrangement can be rotated around a horizontal axis without changing the distance between or positions of the components.

"Readings were taken in the optics dark laboratory at the horizontal position, at 45°, 90° and 180° (upside down). Eventual stray-light was detected by readings from the shaded pyranometer and substracted. All readings were normalized to the horizontal position.

"Conclusions

...Based on our results, we believe that the cosine response is a characteristic of the individual instrument, rather than of a specific brand. Therefore, the cosine response of each instrument should be tested before the instrument is used in the field.

"Furthermore, and in particular, if instruments are supposed to serve as secondary standards, pyranometers to which other are compared, their cosine response [errors] should be no greater than 3% at high angles of incidence. Those pyranometers with cosine responses greater than 3% can, however, be used with good success for the recording of the diffuse irradiance and for this purpose will provide data of acceptable accuracy.

"Instrument calibration constants provided by the manufacturer should be taken cum granu salis. They frequently depend on the climatic area of the factory and on the time of storage and/or history after calibration. At any rate, the calibration constant should be redetermined at a local institution where calibration instruments of high accuracy are available."

Southern California Edison

Rosemead, California

General Description of Facility Procedures

A. Purpose (Charter)

Southern California Edison (SCE), an electric utility company, has the responsibility for calibration, maintainence, and data collection in a solar radiation monitoring network sponsored by WEST Associates (an association of utility companies in the western United States).

B. Normal Tasks

1) Instrument specification
2) Instrument calibration and maintainence
3) Data collection
4) Data publication

CALIBRATION METHODS:

SOUTHERN CALIFORNIA EDISON

SOLAR SOURCE - PYRHELIOMETERS

Calibration of Eppley NIP Pyrheliometers

The best comparison of pyrheliometers are made in sunlight near noon on clear days after they have been mounted on equatorial mountings and allowed sufficient time (30 minutes to 2 hours) to reach temperature equilibrium. Several groups of 20 or more readings can be made in succession to be sure that stabilization has been reached and a good average calibration is obtained.

SCE originally used Eppley Model NIP Pyrheliometer Serial No. 13384E6 as a standard. This pyrheliometer was calibrated originally by Eppley on November 29, 1974. It was cross-checked against JPL's Kendall Mark VI at Table Mountain on April 27, 1976 and against four of JPL's PACRADS on November 29, 1976 at JPL in Pasadena. On March 23, 1977 SCE received a Kendall MKVI Absolute Cavity Radiometer System S/N 67706 which has been the primary laboratory standard ever since. This standard participated in the three intercomparisons of absolute cavity solar radiometers held at New River, Arizona on Nov. 1978, May 1979, and Nov. 1979.

SCE has also made comparisons of the Eppley NIP pyrheliometers in the laboratory using a 1,000 watt quartz-iodine lamp as a radiation source. Agreement within ±1.5% of the sunlight test values was obtained in the test of four NIP pyrheliometers against our standard NIP pyrheliometer. The average agreement of all four was 0.6%-. Further investigation of this laboratory method will be made in order to provide an alternative test method that can be used when weather conditions make outdoor testing in sunlight impractical.

SOLAR SOURCE - PYRANOMETERS

Pyranometers can be calibrated by using either a pyrheliometer or another pyranometer as a standard. When the pyrheliometer is the standard, either the classic sun and shade method, or a collimation tube method can be used.

Sun and Shade Method

The pyrheliometer measures the direct radiation (I). The ZD is measured or calculated from time and location. (SCE built a device to measure ZD within ±0.1°.) From these measurements, (II) the vertical component of the direct radiation is calculated (II) = (I) ZD. The total radiation (IV) is measured with the pyranometer. Then a 10 cm shading disk is held 1 meter away from the pyranometer shading it from the sun. This 1/10 ratio of disk size to distance subtends a 5.7° angle equal to the acceptance angle of the NIP pyrheliometer so that the same amount of circumsolar radiation is blocked as measured by the pyrheliometer. This gives a measure of (III) the diffuse radiation. (II') is calculated by subtracting (III) from (IV).

$$(II') = (IV) - (III) \tag{8}$$

(II') is then compared with (II) as calculated from the reading of the pyrheliometer and the ZD. The percent error of the pyranometer is:

$$\%E = \frac{(II') - (II)}{(II)} 100 , \tag{9}$$

(10) the correction factor is $CF = \dfrac{1}{1 + \%E/100}$,

(11) the new constant $K' = \dfrac{K}{CF}$, where K is the marked constant.

Collimation Tube Method

If the pyranometer can be mounted level inside a box with a collimation tube pointing at the sun, II' can be measured directly.

This method avoids the problem of making two measurements separated in time, but may introduce temperature problems by shading the pyranometer base from the sun.

In both of these methods, the measurement is limited to the ZD of the sun at the time of the test. Tests at different ZDs will be different if cosine errors are present.

Originally, SCE used a collimation box on an equatorial mounting and tilted the pyranometer inside the box for various equivalent ZDs. However, this resulted in systematic errors caused by tilting the pyranometer which affects the air and heat circulation within the unit. SCE now measures cosine response separately.

Calibration by Comparison with a Standard Pyranometer

Pyranometers can be compared directly either in sunlight or in the laboratory by artificial light. However, in the field, the comparison will be affected by the cosine errors of the standard and under test units, and in the laboratory, they will also be affected by any difference in spectral response. For this reason, best results are obtained by comparing units of the same model. SCE uses this method for field-checking its solar measurement stations and has developed a laboratory light setup that can be used when weather prevents outdoor testing. However, the method using the pyrheliometer are considered to be more reliable and are used whenever possible.

Overall Accuracy

At the present time, the overall accuracy of measurements in this field by SCE is estimated to be as follows:

Kendall Mark VI Pyrheliometer System	±0.5%
Calibration of NIP Pyrheliometer by SCE	±1.5%
Calibration of Pyranometer by SCE	±2.5%

Because of cosine errors, the calibration constant of a pyranometer is at best an average value. Units that agree at noon may disagree at 5:00 p.m. Fortunately, the larger errors at greater ZDs occur also at low levels of radiation and so affect the total less.

CALIBRATION METHODS:
SOUTHERN CALIFORNIA EDISON

SOLAR SOURCE

Pyrheliometers

1. Compared in sunlight on an equatorial mounting with Laboratory Standard Kendall MKVI Radiometer System S/N 67706.

2. Compared in sunlight on an equatorial mounting with Laboratory Standard Eppley Model NIP Pyrheliometer S/N 13384E6 at location of installed pyrheliometer using DVM readings.

3. Same as above, but using pulse time readings (data recording system).

4. Compared in the Shop and Test Laboratory with Laboratory Standard Eppley Model NIP Pyrheliometer S/N 13384E6 using a 1,000 watt quartz-iodide tungsten lamp at 120 volts as the radiation source. Comparison by substitution of standard and under test pyrheliometer.

Pyranometers

Calibrations in sunlight using pyrheliometer as the standard:

1. Sun and shade method using Kendall MKVI S/N 67706 as the standard. A 10 cm shading disk used 1 meter away. Readings after two and one-half minutes minimum sun and shade exposures.

2. Collimation box with 3" x 30" collimation tube on altazimuth mounting: pyranometer kept level in box. Using Kendall MKVI S/N 67706 as the standard. Readings after two and one-half minutes exposure, and corrected for two and one-half minutes "dark" reading.

3. Calibration of a pyranometer for relative cosine response with coelostat.

4. Tilt test in sunlight with coelostat.

Calibrations in sunlight using a pyranometer as the standard:

1. On roof of building, unobstructed sky.

2. At field location of installed pyranometer using DVM.

3. At field location of installed pyranometer using pulse time requirements.

Calibrations in artificial light using a pyranometer as the standard:

1. Small portable test box with one 150 W reflector flood lamp. White interior. Stop plates to reduce level of light used at 115 or 120 V regulated voltage. Because of heating effects, readings must be made at 20 time constants. (PSP = 20 seconds, SR-75 = 32 seconds and 8-48 = 75 seconds.) Standard pyranometer must be same model as under test pyranometer. Comparison by substitution of standard and under test pyranometer.

2. Four-light setup with 150 W reflector flood lamps at 30°, 45°, 60° and 75° equivalent ZD at 14 1/2", 18 1/2", 18 1/2" and 15 1/2" respectively. Adjusted to produce best average angular equivalent distribution of light over the year at 34° North latitude. Four 14 watt muffin fans used to cool lamps. Pyranometer on turntable for equivalent azimuth settings. Pyranometer in level position. Standard pyranometer must be same model as under Test Pyranometer. Comparison by substitution of standard and under Test Pyranometer. Tare read after one minute under large foil-covered box. Five minutes, 360° rotational warm-up and one minute between test readings.

3. Cosine response test using 1,000 W quartz-iodide tungsten light at 120 volts. Pyranometer is mounted with its sensor in a vertical position inside the collimation box with the 3" x 30" collimation tube and rotated about the vertical axis to determine relative cosine response. Because of heating effects, readings must be made at 20 time constants. (PSP = 20 seconds, SR-75 = 32 seconds and 8-48 = 75 seconds.)

4. Azimuth response test using one of the four 150 W lamps on the four-light setup. Pyranometer is mounted with its sensor horizontal on a turntable and rotated about a vertical axis. Relative response to the light at 60° or 75° is measured.

Five minutes, 360° rotational warm-up and one minute between test readings.

A PYRANOMETER CALIBRATION BOX TO FACILITATE THE COMPARISON OF A PYRANOMETER WITH A STANDARD PYRHELIOMETER IN SUNLIGHT

Basic Considerations

The classic sun and shade method of calibrating a pyranometer against a pyrheliometer compares the difference between the total and diffuse solar radiation as measured by the unshaded and shaded pyranometer with the vertical component of the direct radiation. This component is calculated from the narrow angle normally incident radiation, as measured by the pyrheliometer, multiplied by the cosine of the ZD of the sun at the time of observation.

An improved method suggested to us by Martin Berdahl of JPL is to use a collimation tube pointed at the sun so that only the direct solar radiation is allowed to strike the pyranometer. (The pyranometer remains in its normal position with sensor horizontal.) Since this is the desired value, only a single measurement is required. It is still necessary, however, to calculate the vertical component of the radiation measured by the pyrheliometer. This required determination of the ZD.

If the pyranometer is mounted inside a closed box rigidly attached to the end of the collimation tube and adjusted at right angles of the axis of the tube, then when the tube is pointed directly at the sun, the pyranometer is receiving the same direct normal incidence radiation that is measured by the pyrheliometer, and no measurement or calculation of the ZD of the sun is required. The acceptance angle of the collimation tube should be the same as that of the pyrheliometer in order that both will see the same amount of sky surrounding the sun.

This pyranometer calibration box can be equatorially mounted and driven at the solar rate to keep the collimation tube pointing directly at the sun. For convenience, the pyrheliometer can be mounted on the outside of the calibration box with its axis parallel to that of the collimation tube, thus eliminating the need for a second equatorial mounting and drive.

This method of calibrating a pyranometer by direct radiation only at normal incidence is only valid if the pyranometer has a reasonably good cosine response and is not sensitive to tilt error. If large cosine errors exist, the calibration will be incorrect for direct radiation at large zenith angles (low altitude angles) and for the components of diffuse radiation at such angles.

The calibration box can be used to check the cosine errors of a pyranometer by arranging for the pyranometer to be tiled at any angle relative to the axis of the collimation tube, thus simulating any desired equivalent zenith angle. The angle of tilt can be read on an attached degree scale. With the pyranometer tilted, its reading is compared with the reading of the pyrheliometer multiplied by the cosine of the angle by which the pyranometer is tilted.

Great care should be used in the construction and adjustment of this equivalent zenith angle scale since a 1° error at 30° results in approximately 1% error in the cosine, while a 1° error at 60° results in an error of approximately 3%. At 80°, a 1° error causes an error of approximately 10%.

The pyranometer mounting can also be arranged so that it can be rotated about an axis at right angles to its base so that the response at various equivalent azimuths can be determined. The response should be the same at all azimuths, but may actually vary in practice. For this scale, reasonable accuracy and 5° intervals are sufficient.

<u>Advantages of this Method</u>

1. A pyrheliometer can be used as the standard. (Best stability.)
2. Calibration is in sunlight. (Little or no spectral error.)
3. No calculation or measurement of ZD required. (Troublesome.)
4. No manual shading disk is used. (Awkward to hold steady.)
5. Not limited to measurement at actual ZD of sun.
6. Can be used to check cosine errors with reasonable accuracy.
7. Not greatly affected by clouds unless near sun.
8. Does not require a 180° unobstructed sky. (Just a clear view of sun.)

Disadvantages of this Method

1. Requires construction of calibration box.
2. Requires equatorial mounting with clock drive suitable for this unit.
3. Requires mounting pyranometer in box for test. (Awkward for installed units.)
4. Not as easily portable as a simple comparison pyranometer.
5. If the pyranometers change calibration with tilt, the method is inaccurate when the pyranometer is not maintained in a horizontal position.
6. Heating effects inside the box can cause errors.

Smithsonian Radiation Biology Laboratory
Rockville, Maryland

General Description of Facility Procedures

A. Purpose (Charter)

The Smithsonian Radiation Biology Laboratory has been aware, for a long time, of the need to know basic solar parameters to a "high resolution" as they relate to science, engineering, meterology, photobiology, medicine, and agriculture. Measurement and system design has continued for a number of years and provided accurate standards, precise data and monitoring system designs which require a minimum of maintainence.

B. Normal Tasks (Procedure)

1) Standards laboratory
2) System designs
3) Data collection

C. Related Tasks (Special Procedures)

Spectral distribution studies of total solar energy versus time of year for Rockville, Maryland; Barrow, Alaska; Panama City, Panama; and Israel.

E. Number of Personnel

Smithsonian personnel include highly qualified administrators, research directors, scientists, engineers, and technicians.

The Smithsonian Institution was among the first organizations in the world to implement a regular program of measuring solar radiation. They have always been at the forefront pushing the technology of solar radiation measurement.

The function of solar radiation measurement today is done in a laboratory separate from the large complex of museums we now think of as the Smithsonian. This laboratory is called the Smithsonian Radiation Biology Laboratory, (SRBL).

A variety of research programs are pursued by SRBL throughout the world. A network of stations measuring the available total horizontal solar radiation in six different spectral regions is maintained. These stations are located at artic, temperate, and tropical sites in order to identify the range and amount of spectral variation in solar radiation. The primary instrument is the Eppley PSP. This instrument is sometimes modified in order to satisfy the special requirements of SRBL.

Calibration procedures at SRBL are commonly tailored to a specific experiment, and the optical laboratory resources there.

Standards Maintained

		Models	Serial No.
A. Absolute Insts.			
	1. Pacrad	1.	1.
	2. Abbot (convertible pyranometer)	2.	2. T-5
B. Pyrheliometer			
	1. Silver Disc	1.	1.
	2. Abbot (convertible pyranometer)	2.	2. T-5
C. Pyranometer			
	1. Abbot (convertible pyranometer)	1.	1. T-5
	2. Eppley	2. PSP	2.

Instruments Normally Calibrated

	Absolute (Relative to Absolute Standard)
Pyranometer (no filter)	
1. Eppley PSP	±2%
Pyranometers (w/filter)	
1. Eppley PSP	

Note: A variety of instruments for measuring solar radiation are maintained and calibrated when necessary. The nature of the research at SRBL requires a much greater variety of instruments than is normally considered in estimating the solar resources for the purposes of energy.

CALIBRATION METHODS:
SMITHSONIAN RADIATION BIOLOGICAL LABORATORY
ROCKVILLE, MARYLAND

SOLAR SOURCE - PYRANOMETERS

Detectors

The Eppley precision pyranometers were purchased with calibrations on the International Pyrheliometric Scale of 1956. The calibrated sensitivities of these instruments average about 4 mv cal^{1} em^{2} min^{1}. The calibration performed by Eppley is checked at the Smithsonian Radiation Biological Laboratory. The calibrations at the Eppley Laboratories are usually done at relatively high levels, about 0.5 ly min^{1} (0.5 cal cm^{2} min^{1}). Since the instruments are also used for lower levels of irradiance, it is necessary to calibrate all new detectors at various irradiances against a standard instrument, as well as to make an intercomparison among instruments. The temperature compensation of the detector is quite effective and yields a zero output voltage at zero input light levels over the temperature range of -40°C to +40°C.

The time constants of the instruments have been verified. The time constant for equilibrium was found to be about six seconds on the average and the longest to be seven seconds. A time constant of this order is required because of the method used in making measurements to obtain 100 nm broad band spectral data.

The instruments measure global irradiance on a horizontal surface. The black circular receiver, approximately 1 cm in diameter, is covered with two domes. The small inner dome is WG 7 clear glass and the outer large dome is colored to yield the proper short wavelength cutoff. There are six instruments used and, therefore, six domes with the following wavelength pass bands:

WG 7	290 nm - 2.8 μ
GG 400	400 nm - 2.8 μ
GG 495	495 nm - 2.8 μ
RG 610	610 nm - 2.8 μ
RG 715	715 nm - 2.8 μ
RG 805	805 nm - 2.8 μ

Acquisition System

The data acquisition system consists of a digital voltmeter, scanner, a digital clock and an output recorder. The system collects data for each waveband every three minutes from sunrise to sunset throughout the year.

The scanner is a high-speed unit with very low thermal offset and contact voltage, thus permitting microvolt measurements. The output voltages from the detectors are routed by the scanner to the voltmeter, which converts them to digital form for further processing by the system.

The digital clock is used to put onto tape the standard time of each scan, as well as initiating the scan every three minutes.

Calibration Procedure

The total system is calibrated at regular intervals in order to insure a reliable absolute measurement. The detectors, although calibrated by the manufacturer, are recalibrated at the Smithsonian Radiation Biological Laboratory and instrument intercomparisons are made. Because the narrow band spectral readings are obtained by subtracting adjacent broad band readings, small errors can be magnified many times. Two different substandards are maintained at the Smithsonian Radiation Biological Laboratory to verify the accuracy of the detectors. One of these is calibrated on the International Pyrheliometric Scale of 1956 and is an Eppley precision pyranometer, the others are an Abbot pyranometer calibrated on the Smithsonian scale of 1913 and a silver disk also on the 1913 scale. Comparisons between the two pyranometers agree to within .5% when adjusted from one scale to the other. These two instruments are used for checking the detectors in the monitoring system. The ratio between the two scales has generally been accepted as 2.5%. Two independent comparisons, one at the Smithsonian and one at the Eppley Laboratory, agree to ±.25%.

The comparison of the instruments is always made with the standard pyranometers connected to the acquisition system. This keeps instrumental error to a minimum. Also, a comparison of the time constants between the Eppley pyranometer and the Abbot type show they are the same.

As previously mentioned, the time constant of the pyranometers is about six seconds for 100% response. If the sky is changing at a rate of 1 ly min^{-1} min^{-1}, then the time between consecutive readings of 0.1 seconds will cause an error in the readings of only one part in 600 and for a time difference of 0.6 seconds, an error of 1%. To keep such errors to a minimum, we generally calibrate only on cloudless days. The normal RMS errors in the broad band readings are

$$\text{Error} = \sqrt{E_c^2 + E_t^2 + E_f^2} = \sqrt{3} = 1.7\%$$

where

E_c = calibration error = 1%

E_t = time difference error = 1%

E_f = filter factor error = 1%

From the narrow bands (100 nm), the errors are larger because they are the RMS errors of adjacent broad band values. The best possible error then would be $\sqrt{6\%}$ = 2.4%. No matter how carefully one calibrates and compares, other errors are present in the system. These include noise, the least significant digit on the voltmeter, the cosine errors in the double domes and some errors due to wind, etc. These, added to the 2.4% error, can produce much larger errors at low levels because they do not represent percent, but absolute errors in terms of ly min^{-1}.

The noise level in the system is ±1 μvolt, the least significant digit is ±1 μvolt and the environmental effects cause about ±1 μvolt error. These add up to ±3 μvolts or about 0.002 ly min^{1}. When telescoping mast is used for sunrise and sunset readings, an additional ±2 μvolts of noise can be introduced due to the 1°-2° sway of the mast which which increases the normal noise level to 3 μvolts. This means our low level error is now on the order of 7 μvolts or .005 ly min^{-1}. The real effect of the cosine correction has not been determined for low solar elevations, but it appears to be on the order of 5 to 7%.

Each of the outer domes, which are filters, must have their transmissions determined to correct the instrument constant for that specific filter. This correction is necessary because all the instruments are calibrated with clear WG 7 domes. The filter factors (F.F.) are by definition

$$F.F. = \frac{\int_{\lambda_1}^{\lambda_2} H_\lambda \, d\lambda}{\int_{\lambda_1}^{\lambda_2} H_\lambda \, \tau_\lambda \, d\lambda} \tag{1}$$

where $H\lambda$ is the irradiance at wavelength at the top of the atmosphere, $\tau\lambda$ the transmission of the filter at wavelength λ, and λ_1 and λ_2 are limits of the pass band of the filter. Curves to determine $\tau\lambda$ are obtained from a Cary 14 recording spectrophotometer. Then if the F.F. is applied in the following manner

$$C^* = \frac{C \times F.F.}{1.083}, \tag{2}$$

the constant C* is obtained that must be used to reduce the output voltages to ly min^{-1}. The terms are defined as follows:

C* = multiplication factor in ly min^{-1} $volt^{-1}$

C = original calibration with WG 7 dome

1.083 is the transmission correction of a WG 7 dome

Errors

The total errors of any system can be determined only by the accuracy and precision of the data output of that system. Estimates and calculations can be made, but only a lower limit or least error can be determined this way. The problem of error determination is now new, but one which becomes more difficult as instrumentation becomes more complex. Another source of error is the F.F. as determined by Equations (1) and (2). The Cary 14 is accurate to ±1%; therefore, by using these curves and the solar output at the top of the atmosphere as the source, we expect very small errors. After the F.F. had been calculated, a direct determination of the filter transmission was made, the sun being used as a source. The use of double filters with the same cutoff at λ_1 and λ_2 were used. Since the solar beam is fairly well collimated, the limiting aperture is the receiver which in this case is a thermopile. A comparison of measured and computed F.F.'s showed less than 0.25% difference in the two. Therefore, addition of a 1% F.F. error is not from determining the F.F., but from environmental causes such as soot, dust, etc.*

*Solar Radiation Measurements/1968-1973, pub. Smithsonian Radiation Biology Laboratory/Rockville, MD.

The Eppley Laboratory, Inc.
12 Sheffield Avenue
Newport, Rhode Island 02840
Tel: (401) 847-1020

General Description of Facility Procedures

A. Corporate Description

The Eppley Laboratory has developed a strong radiometry division which can perform numerous scientific services in radiometric fields. These services include the measurement, analysis, production, regulation, modification or isolation of thermal radiation. Eppley Laboratories has been manufacturing solar radiation monitoring instruments for many years. That experience has developed an in-depth expertise in the design, manufacture and evaluation of solar radiation measuring instrumentation.

B. Personnel

1. Meterological staff
2. Source examination group
3. Instrumentation development group
4. Calibration staff

C. Products

1. Eppley Pyranometer Model 8-48
2. Eppley Pyranometer Model PSP
3. Eppley Pyrheliometer Model NIP
4. Eppley Infared Radiometer
5. Eppley Hickey-Frieden Absolute Cavity Radiometer Model H-F
6. Eppley Ångström Pyrheliometer
7. Eppley Ultraviolet Radiometer
8. Eppley Shadow Band Standard Model SBS

Calibration Methods:

Normal Incidence Pyrheliometers (NIP) - All NIPs are calibrated in sunlight, and tested for their temperature response throughout the range specified.

Precision Spectral Pyranometer (PSP) - Most PSPs are calibrated indoors in an integrating hemisphere, against a working standard of identical type and surface coatings. All instruments are checked for temperature response.

8-48 Pyranometers (black and white) are calibrated in the integrating hemisphere. Samples of the production are checked for temperature response to assure consistency.

Temperature testing is performed in a temperature chamber with the instruments illuminated by a lamp in the chamber itself. Illumination is monitored to assure stability.

Intercomparison of instruments of different types or with different coatings is always done in sunlight on a good day.

Eppley Laboratories staff participate in most (if not all) national and international intercomparisons of absolute and standard instruments.

Calibration Facilities:

The primary non-standard facility is the integrating hemisphere. This was described in considerable detail by Drummond and Greer.*

*A. J. Drummond and H. W. Greer, "An Integrating Hemisphere (Artificial Sky) for the Calibration of Meterological Pyranometers," Solar Energy, V. 10, No. 4, 1966, pp. 7-11.

HY-CAL Engineering
12105 Los Nietos Road
Santa Fe Springs, California 90670
Tel: (213) 698-7785

General Description of Facility Procedures

Corporate Description

A. Corporate Description

In recent years, HY-CAL Engineering has applied its experience in thermal technology to the development of instruments and systems to obtain accurate data on heat and temperature. This information has been used to measure and control the effects of thermal factors on men, materials, equipment, and structures.

B. Products

1. Pyrheliometers, D-8400 series
2. Pyranometers, P-8400 series (hemispherical view)
3. Radiometers, R-8000 series

C. Standards

The test and calibration laboratory is fully equipped with certified, test and calibration instruments and equipment. Many of these instruments were developed and perfected wholly by HY-CAL, and today are established as standards for the thermal instrumentation field. All calibration and testing is traceable to the National Bureau of Standards.

Laboratory facilities are available for creating various types of thermal test environments, including a temperature range from +4500°F to -452°F. Programmed heating rate test and calibration facilities consist of the HY-CAL RF-10 Radi-Flux® Calibration Facility, convective energy source, precision temperature baths, HY-CAL RB-12 Black Body Source, cryogenic test facility, HY-CAL RT-14 thermocouple calibration facility, plus extensive associated instrumentation and standards.

Prior to delivery, every HY-CAL thermal instrument is carefully inspected, tested, individually calibrated, certified and traceable to NBS. Thermal instruments are only as accurate as their calibration. HY-CAL offers you the most complete, respected and accepted calibration facilities in the nation.

CALIBRATION METHODS:
HY-CAL ENGINEERING, INC.
12105 LOS NIETOS ROAD
SANTA FE SPRINGS, CALIFORNIA 90670
213/698-7785

HISTORY OF CALIBRATION METHODS

In tracing the history of heat flux calibration, it is necessary to illustrate the different methods of generating a heat source and to discuss the mode of heat transfer that was used.

METHOD 1 - STEAM AS A HEAT SOURCE

Case 1 - Conduction

In this method (Figure B7), steam is used as a heat source and cooling water is used as a heat sink. The mode of heat transfer is by conduction. It is necessary with this method to measure the enthalpy of the steam, and the weight of the steam before and after it enters the heat source. Similarly, the weight, temperatures (T_1 and T_2) are also measured to calculate the heat absorbed by the cooling water. Since a perfect insulator does not exist, error is introduced in the calibration via heat loss through the insulation. Other errors will be introduced in the measurement of enthalpy, thermal conductivity, the weighing of water and in trying to establish a steady state with this system. Therefore, in standardizing this method, errors are introduced that are difficult to measure and assumptions could lead to loss in accuracy.

Case 2 - Radiation and Convection

The radiation and convection method (Figure B8) is similar to Case 1 (head conduction method), except that the transducer is not making physical contact so that heat transfer from the surface at temperature T_4 is due to radiation and convection. The receiver surface is kept at a constant temperature by means of cooling water. Case 2 has some of the disadvantages of Case 1. In addition, it has the disadvantage of having to determine the film coefficient of heat transfer between the interface. This method could not be standardized because it is not possible to obtain reproducible results.

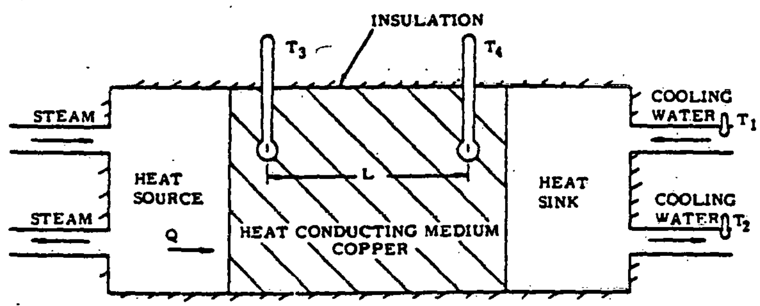

FIGURE B7. Conduction - Steam as Heat Source

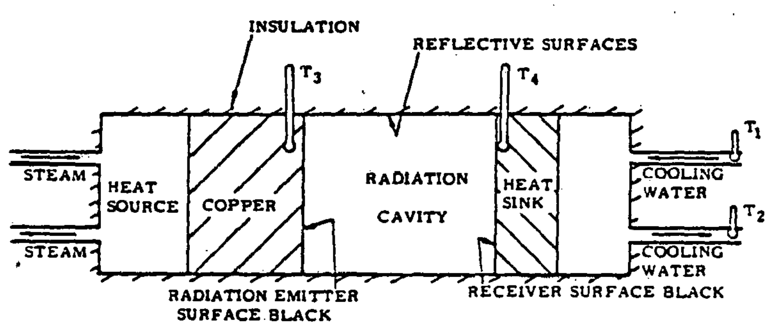

FIGURE B8. Radiation and Convection - Steam as Heat Source

Case 3 - Radiation

Radiation can be used as a source in Figure B8 by installing a window between section 2 and the transducer, or by placing the entire setup in a vacuum chamber. While radiation has advantages over convection and conduction, the method itself still is not a good system due to the indeterminate errors introduced by the insulation, the difficulty of determining the steam enthalpy and weight, and the heat-transfer coefficient to the material. However, because of the design of the three systems shown where accurate control of the heat flux being delivered by the steam is not possible, none are practical as presented for use as heat flux calibration standards.

METHOD 2 - ELECTRIC POWER AS HEAT SOURCE

By replacing the steam heat source in Figure B7, with an electric heater it is possible to achieve a steady state condition. In this method (Figure B9), the electric heater gives accurate control of heat input by the measurement of voltage and amperage rather than steam enthalpies. Therefore, using electric power as a heat source is superior to that of using steam because it will have better accuracy; however, it still has the disadvantage of heat loss through the insulation that is difficult to account for. The inaccuracies encountered were found to be too great for requirements of heat flux transducer calibrations.

The radiation method with electric power as the heat source (Figure B10) has the same disadvantages as those of Method 1.

METHOD 3 - IMAGE ARC AS HEAT SOURCE

This method consists of focusing a carbon arc by means of two parabolic mirrors (Figure B11). It is impractical to conduct a thorough analysis of this setup for the following reasons:

1. Energy losses from mirrors cannot be calculated with any accuracy.

2. Energy flux on the target is not uniform because the arc is essentially a point source, whereas the transducer is not.

3. Reradiations from different parts of the setup cannot be calculated.

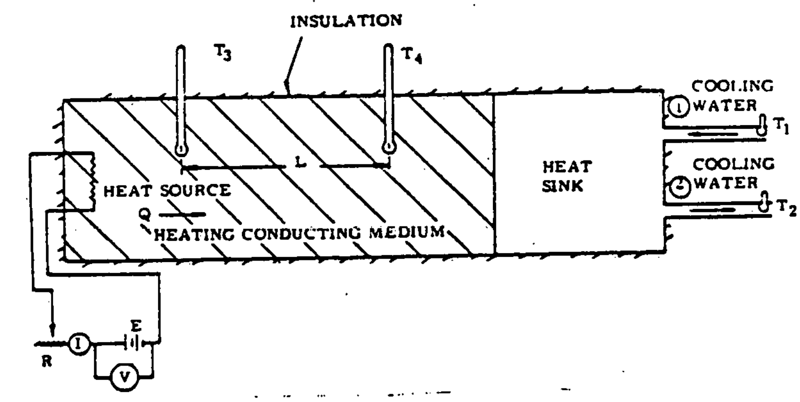

FIGURE B9. Conduction - Electric Power as Heat Source

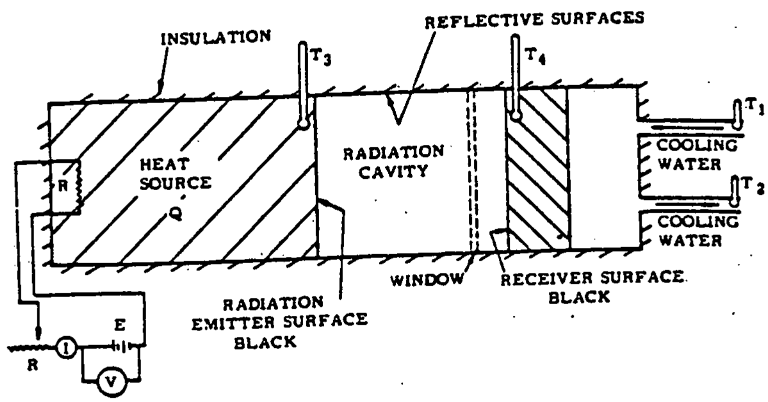

FIGURE B10. Radiation - Electric Power as Heat Source

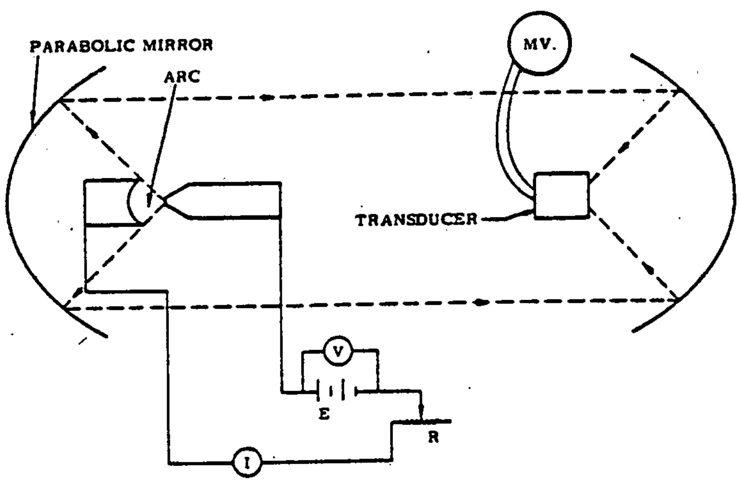

FIGURE B11. Imaged Arc as Heat Source

4. Using an Asymptotic Rapid Response Calorimeter, it is possible to demonstrate that the arc pulsates and takes time to achieve steady state.

5. Nonuniformity, which could lead to errors, is also contributed by the shadow of the arc itself.

Since it is impractical to do a theoretical analysis due to those errors inherent in this method, it would also be impractical to use such a system as a standardized heat flux facility.

METHOD 4 - QUARTZ LAMP AS HEAT SOURCE

This method (Figure B12) is basically similar to Method 3. The source of radiant heat flux consists of a number of lamps focused on the target area by means of a reflector. With the development of the Asymptotic Calorimeters, it was possible to monitor the quartz lamp. It was discovered that it takes considerable time to reach a constant flux condition. Uniformity of radiation flux was improved by introducing an integrator between the quartz lamps and the target area. However, this system was not sufficiently uniform and stable to be satisfactory for calibration.

METHOD 5 - RESISTANCE HEATING AS A SOURCE OF HEAT

One of the major problems encountered in Methods 3 and 4 was to obtain uniform heat flux from the heat source that was reproducible and traceable to a known standard. This problem was alleviated somewhat by mounting a carbon cloth between two electrodes and passing a current through it to obtain the desired temperatures. This method depended on the carbon cloth giving a uniform radiant heat flux. Any change in thickness of the carbon cloth or localized deterioration causes a significant temperature gradient across the surface of the carbon cloth. Consequently, this results in hot spots and nonuniform radiant heat flux. Due to the low heat capacity of the carbon cloth, it is an unstable system; additionally, small changes in the surrounding environment or power input causes significant fluctuations in radiant heat flux.

To overcome the problems of carbon cloth, the cloth was replaced by a graphite plate. The graphite plate is mounted between two

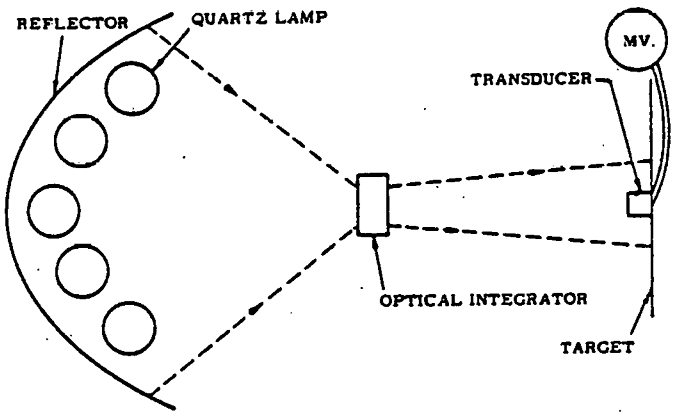

FIGURE B12. Quartz Lamp as Heat Source

water-cooled electrodes. When the power is supplied to the electrodes, it heats the graphite plate resulting in a temperature distribution as shown in Figure B13. The temperature varies with the length of the graphite plate. The temperature profile depends on controlled cooling at the ends of the graphite plate. The heat flux emitted, therefore, depends on installing the block indentically each time. The inaccuracies of the first four systems have been eliminated by this method; only the problem of variations in temperature profile remains.

METHOD 6 - RADIANT HEAT FLUX CALIBRATION SYSTEM

HY-CAL's heat flux calibration system has evolved from the first five methods. The development of this system was a result of overcoming the disadvantages encountered in the first five methods without creating new problems. It was determined that the most reliable, accurate and precise calibration could be achieved by a radiant heat source of uniform temperature-controlled by a stable power supply that could be traced to a known standard.

The result of this development was HY-CAL's RF-10 Radiant Heat Flux Calibration Facility* (Figure). The heart of this facility consists of a specially designed and machined graphite carbon block that is connected between two high-current temperature-controlled electrodes. When a current (closely controlled by ignition) is passed through a block, it heats the block to the desired temperature. Uniformity of surface temperature (Figure B14) is achieved by the special shape of the block and installation is not critical. Since temperature uniformity is the greatest in the middle of the block, only the center portion is used for calibration purposes. The symmetrical graphite block emits heat flux equally on both sides. A nonreflective water-cooled housing is used to prevent reflections and to uniformly absorb the heat flux. This structure is also identical on both sides and is used to accurately position the transducer with respect to the heat source. This calibration system is capable of calibrating continuously from a few hundredths of a solar constant up to several hundred Btu/ft^2-sec.

*Patent 3, 318, 134.

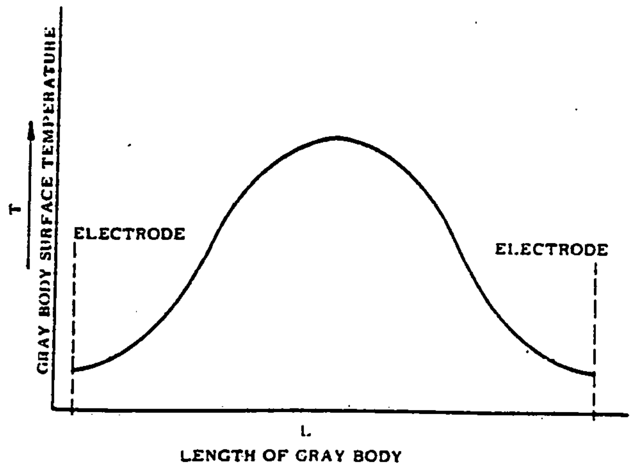

FIGURE B13. Surface Temperature vs.
Length for a Gray Body

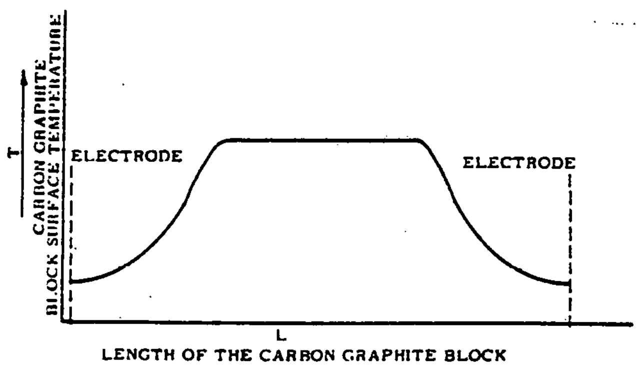

FIGURE B14. Surface Temperature vs. Length
for HY-CAL Carbon Graphite Block

This system approaches the ultimate in the control of block emissivity, interior reflections, uniformity of temperature and view factors. It is, however, a grey body and the Stefan-Boltzmann Equation is not 100% applicable. NBS's traceable blackbody accuracies are transferred to the grey body, eliminating the discrepancies of the grey body.

HY-CAL has developed a special blackbody with an emissivity of 0.99 or better. A precision transfer radiometer is used to transfer the accuracy of the blackbody to the RF-10.

The blackbody (Figure B15) consists of two identical cavities approximately 1 ft. deep and made from graphite. The outside of this graphite is protected by high-temperature insulation which, in turn, is reinforced by a steel cover. The outer surface of the steel cover is then water-cooled (Headpiece).

The blackbody is heated by the same power supply source as the graphite carbon block of the RF-10. The power is controlled by ignition techniques to achieve any desired temperature of the cavity up to 5,000°R. The temperature of the blackbody is measured by a precision optical pyrometer certified by NBS. Thus, the temperature of the blackbody and its resulting radiant heat flux is known to a specified accuracy.

STANDARD CALIBRATION METHOD

The calibration procedure used achieves accuracies within 3% and precision within 0.5%, as traceable to NBS. The procedures include:

1. Calibration of transfer radiometer
2. Calibration of the RF-10 radiant heat flux facility
3. Calibration of primary standard
4. Calibration of customer's calorimeters

SUMMARY

Calorimeters have been developed to a high level of dependability and long-term reliability. However, as with most precision energy transducers, the output characteristic depends on its geometrical and metallurgical properties. Hence, for absolute performance, as opposed

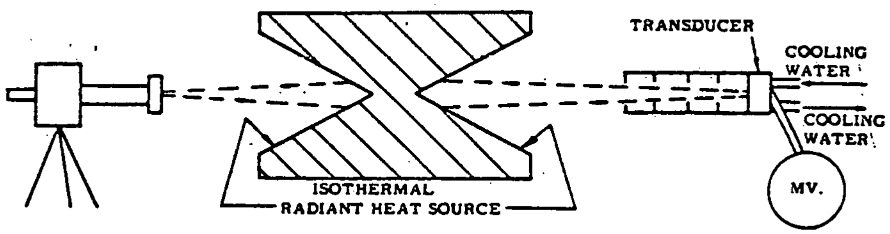

FIGURE B15. HY-CAL Blackbody Standard Heat Radiant Source to relative measurements, the accuracy of the instrument is only as good as its calibration with respect to an absolute standard.

Many of the prior art calibration systems are tied to temperature-measuring techniques, and systems are unwieldy and result in a compromise in accuracy and repeatability unless operated by skilled personnel.

The RF-10 calibrating system, used in conjunction with the black-body transfer, provides the most accurate and convenient method of calibration today.

The pyrheliometer calibration process and traceability to standards at HY-CAL is illustrated in Figure B16.

Note that comparison also provides traceability to WMO while the system described above provides a permanently available reference that is absolute in terms of radiation levels and independent of the sun.

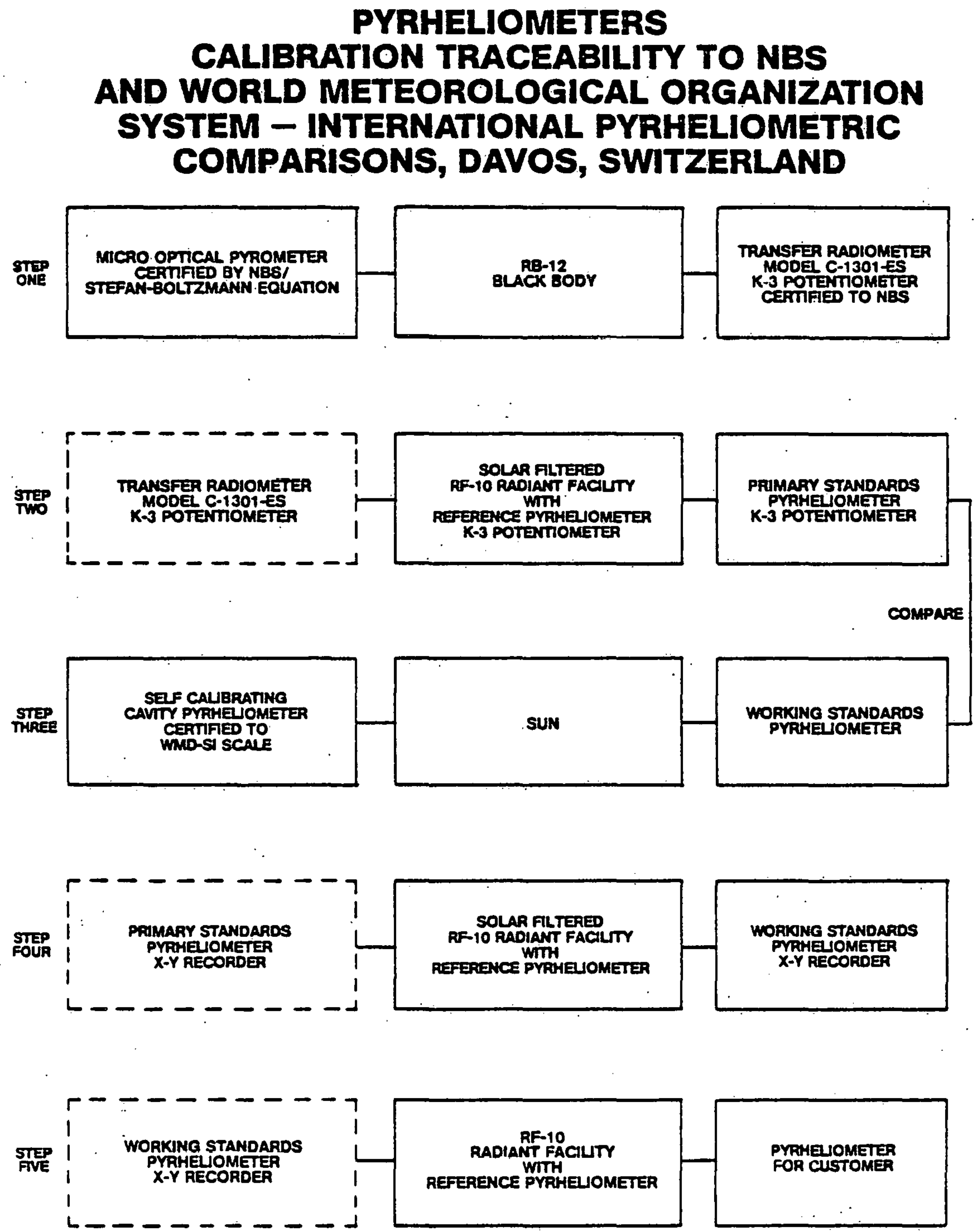

Figure B16. NBS traceability diagram for HY-CAL engineering pyrheliometers.

Desert Sunshine Exposure Tests, Inc.

Box 185 Black Canyon Stage
Phoenix, Arizona 85020
Tel: (602) 465-7356

General Description of Facility Procedures

A. Corporate Description

Desert Sunshine Exposure Tests, Inc. is an internationally known outdoor materials and solar devices test laboratory. Services provided not only include testing but also calibration, weather measurement with magnetic tape storage, solar measurement, and data base packages which include a statistical mapping of the United States.

B. Standards

Hickey-Frieden absolute cavity pyrheliometer which has been compared to the US/NOAA Kendall PACRAD, an Eppley Ångström pyrheliometer and an Eppley-Kendall PACRAD, are three directly traceable to the International Pyrheliometric Conference I.P.C., IV.

C. Intercomparisons of Absolute Instruments

The Desert Sunshine Exposure Test Laboratory has hosted three intercomparisons of absolute cavity standard radiometers. These were Nov. 1978, May 1979, and Nov. 1979.

Special observing facilities were constructed at New River, Arizona just for this purpose.

The results of these intercomparisons indicate that the new cavity radiometers are stable instruments to better than 0.5%.

LI-COR, Inc.

4421 Superior Street
Lincoln, Nebraska 68504

General Description of Facility Procedures

Corporate Description

LI-COR started business in 1971 (as LAMBDA Instrument Corp.). For nearly two years, the company consisted primarily of the now president, William Biggs, his wife, Elaine, and several interested scientists and technical people whose encouragement resulted in development of the present product line. In 1973, a professional nucleus was hired consisting of scientists and engineers. Those key individuals who remained with the company enabled rapid growth "while maintaining instrument quality and customer service excellence."

Management and Personnel

President: William W. Biggs (President, Lambda Instrument Corp.), MSEE with extensive experience in instrumentation research and development, specializing in electro-optics and agricultural research.

Products

1. Radiation sensors; meters and integrators
    a. photosynthetically active radiation
    b. "light" as seen by human eye
    c. solar energy
2. Pyranometers - silicon photovoltaic detector
3. Photometric sensors (silicon)

Standards

The photometric sensors are calibrated against working quartz halogen lamp standards which have been calibrated against laboratory standards supplied by the N.B.S. Standard lamp current is metered to 0.035% accuracy.

Instruments Normally Calibrated

	Accuracy (est.) Absolute (Relative to Absolute Standard)	Short Term Relative Error (Between Instruments) same source as calib.*	other source than calib.**
Pyranometer (no filter) and Photometric			
1. LI-200S (pyranometer)	± 5% Eppley	± 5%	NA
2. LI-2105 (photometric)	± 5% NBS	± 1%	<± 7%
3. LI-212S (underwater photometric)	± 5% NBS	± 1%	<± 7%
4. LI-220S (I.R.)	± 5% NBS	± 1%	<± 7%
5. LI-190SE (photosynthetic irradiance)	± 5% NBS	± 1%	<± 7%
6. LI-190S (Quantum)	± 5% NBS	± 1%	<± 7%
7. LI-192S (underwater quantum)	± 5% NBS	± 1%	<± 7%

*The pyranometer error is higher due to the differences in construction and response (compared to Eppley) as well as the changeable nature of the sun and sky radiation even under good conditions.

**This error is caused by non-ideal spectral response and is typically, but not always, within the range shown.

CALIBRATION METHODS:
LI-COR, INC.

CALIBRATION PROCEDURE FOR LI-COR SILICON CELL LIGHT SENSORS

Determination of the calibration constants of quantum and photometric sensors is done on a specially equipped optical bench. The radiation source is a type DXW 1,000 watt quartz-halogen lamp mounted in a precise orientation and energized with a highly regulated direct current source, an Optronic Model 83DS which also provides controlled warm-up to the lamp. Current is monitored with a Leeds and Northrup Model 4222-B precision shunt (having + or - 0.001% accuracy), and a Hewlett-Packard Model 3465A digital voltmeter to provide a current of 8.000 amps + or - 0.035%. This contributes less than a 0.25% error component to the lamp irradiance in the wavelength range of 400 to 700 nanometers. At a distance of 50.00 cm, the output of a stable EG&G silicon photodiode is frequently measured as a system check. Approximate color temperature of the lamp is 2,850° Kelvin.

The calibration lamp is calibrated by comparisons with two standard lamps, Optronic Models 200CP, which are identical type lamps operated at identical current as the calibration lamp. After the lamp is seasoned, it is calibrated by comparing readings taken with a series of different types of sensors to the readings obtained from the standard lamps and calculating the correct conversion factors. These factors compensate for the slight differences in filament configuration and color temperature of the lamps, and provide good results for sensor types used in the comparisons. Using computer-generated curve fit values of spectral irradiance for the standard lamps, the output of the lamps in quantum and photometric units is calculated. The conversion factors then are used to define the output of the calibration lamp.

Integrals used to find the lamp output in quantum units of microeinsteins per square meter per second are of the form:

$$\mu E = \frac{1}{Bhc} \int_{400\ nm}^{700\ nm} W(\lambda)\ \lambda\ d\lambda$$

where B = 6.025E + 17 photons per microeinstein;

where λ is the wavelength, and hc (Planck's constant times the speed of light) equals 1.9862E-16 Joule-nm / photon and W (λ) is the spectral irradiance of the lamp in watts per square meter per nm. To find the photometric output in lux, the integral is of the form shown where 680 (683 after June 1, 1978) is the luminous efficacy at 555 nm and y (λ) is the luminosity coefficient of the CIE Standard Observer curve.

$$\text{lux} = 680 \int_{400\ \text{nm}}^{700\ \text{nm}} W(\lambda)\, y(\lambda)\, d\lambda$$

The value computed by LI-COR, the value measured by Optronic Laboratories and the value determined by the National Research Council, Canada, for one of the standard lamps were all within + or - 1%. However, the accuracy as applied to sensor calibrations is taken to be + or - 3% due to uncertainties of the national standards, transfer uncertainties, stability, and spectral irradiance uncertainties. LI-COR specifies an accuracy of + or - 5% to the National Bureau of Standards' (NBS) sources for calibration of photometric and quantum sensors.

Other errors which add to the uncertainty of calibration are kept low by the use of suitable equipment and methods. All sensor readings are taken by amplifying the signal with a chopper-stabilized amplifier and reading the output on a digital voltmeter. The error contributed by this is less than 0.15%. The positioning of the lamp and sensors is adjusted precisely by laser alignment methods to achieve the correct horizontal, vertical, and rotational orientation. When this is accomplished, the spacing between the lamp and sensor is adjusted by a microscope and vernier to be 50.00 cm + or - 0.1 mm. The resultant error due to the physical setup is less than 0.1%. Stray light in the 400 to 700 nm wavelength range is kept to less than 0.1% by the use of black baffles and black velvet surrounding the calibration setup.

A selectable filter station is mounted on the principal baffle and contains filters simulating several spectral sources. It is used with each sensor to check for acceptable spectral response variations. Periodically, sampled sensors, as well as all sensors ordered with "A" curves, are given a more rigorous test to determine their relative spectral response. By using computer analysis to select appropriate filter glasses, as well as continuous testing, sensors are produced which closely match the ideal quantum response and the CIE photopic response. Sensor errors under various types of common illumination sources are calculated by computer also. This test can also indicate the excessive errors which occur when using the wrong sensor type for making a particular measurement.

Equipment used to obtain the spectral response includes the Optronic precision current source used to provide constant current to a quartz-halogen lamp. This is the illumination source for a Heath EU-700 series monochromator which is adjusted for a 2.5 nm bandwidth. Readings for the sensor being tested and for an EG&G UV100B photodiode are recorded every 10 nm. The diode has been calibrated against a blackened thermopile traceable to the NBS.

Using the values of responsivity R (EG&G) of the calibrated photodiode and the readings from the monochromator of both the calibrated diode Q (EG&G) and the test sensor Q (SEN), the relative response then is R(SEN) = R(EG&G) Q(SEN)/Q(EG&G). The relation describing the whole system is $Q(\lambda) = R(\lambda)\ W(\lambda)\ M(\lambda)$, but the last two functions of the lamp and monochromator are constant for the test. This computation done for each wavelength and normalized to unity (100%) yields the relative spectral response $r(\lambda)$.

"A" curve calibrations also include the peak absolute sensitivity, Ks, of the sensor. This is determined from the known spectral irradiance, $W(\lambda)$, of the calibration lamp and the output current, I, produced by the sensor when illuminated by the lamp. Then

$$I = Ks \int W(\lambda)\ r(\lambda)\ d\lambda$$

Ks is determined by a discrete summation for intervals of 10 nm using the known values and giving results in amps per watt per square cm. The absolute spectral responsivity then is $Ks\ r(\lambda)$.

Pyranometer sensors are calibrated outdoors on clear days at approximately solar noon during the spring and summer months by comparison with an Eppley precision pyranometer, Model PSP, traceable to NBS. The sensors are all maintained level and kept free from overhead obstructions and stray light. Tests conducted with LI-COR integrators and pyranometers showed good agreement of daily insolation totals compared to the Eppley instrument. When winter calibrations are necessary, an alternate technique may be employed. The Eppley PSP and test sensor are mounted on a platform so as to be in a common plane, this plane being oriented approximately perpendicular to the sun. As this procedure is subject to errors caused by ground reflection, it is used only if good correlation is achieved with a set of reference sensors which have previously been calibrated in the normal horizontal orientation. The advantage of this method is reduction of possible cosine related errors due to the low zenith angle of the sun. (The tilt error for the PSP is negligible.)

Molectron Corporation

177 North Wolfe Road
Sunnyvale, California 94086
Tel: (408) 738-2661

General Description of Facility Procedures

A. Corporate Description

Molectron Corporation produces a pyroelectric radiometer designed to provide accurate measurement of radiant power from the vacuum ultra-violet range to the far infrared. The heart of the radiometer is a rugged, permanently-poled lithium tantalate crystal coated with a stable black absorber. The radiometer is capable of reading nano-watts up to 50 watts/cm^2.

B. Special Features of the Molectron Pyroelectric Radiometer are:

1. Internal calibration
2. Mechanical chopper, interchangeable windows
3. Electronic null for elimination background
4. Analog and digital readout
5. Isothermal probe turret

C. Standards

Calibration of each instrument is done internally by use of a high intensity L.E.D. which is traceable to NBS standards.

CALIBRATION METHODS:
MOLECTRON CORPORATION
177 NORTH WOLFE ROAD
SUNNYVALE, CALIFORNIA 94086
408/738-2661

Calibration Procedure for Molectron PR-200 Radiometer

INTRODUCTION

At this time, the accepted procedure for calibrating radiometric systems is to use an NBS traceable standard of total irradiance. The detector or radiometer probe is placed at some specified distance from the lamp (where the level of irradiance is well-known), and the detector output noted or, as with the PR-200, the system gain is adjusted so that the digital reading coincides with the known lamp irradiance at the detector.

The lamp has been calibrated by using a calibrated blackened detector (typically a thermopile) which sees all the radiation from the lamps incandescent filament, along with the radiation from the hot quartz bulb enclosure. Errors on the order of 8 to 12% can result if one adjusts the gain of a quartz-windowed probe (which does not see all of the radiation from the lamp) to give the same reading that one would expect from a blackened windowless probe which does see all the radiation. Therefore, it is best to adjust the gain of a windowless probe to achieve the proper output and then, when different windows are used, to change the gain around this known point, rather than to first adjust the gain using a quartz-windowed probe and then to change gain around this more inaccurate point.

TYPE AND CARE OF LAMPS

The in-house standard for calibrating the Molectron PR-200 is a 200 watt, tungsten-halogen lamp standard of total irradiance supplied by Optronic Laboratories. From this in-house standard test, lamps are calibrated and routinely checked for daily use in calibrating the PR-200 systems. These test lamps are commercially available, type DXW, quartz-halogen, tungsten coiled-coil filament lamps.

The following precautions should be noted when working with these commercial lamps.

1. These lamps have a small drift of output with lifetime. Therefore, the expensive standard supplied by Optronic Laboratories should be used sparingly to prolong its useful life, the daily use secondary standards, should be periodically checked against the in-house standard, and no lamp should be used for more than 50 cumulative hours.

2. In no case should one's fingers come in contact with the quartz envelope of the lamp, whether hot or cold. Permanent etching of the lamp envelope that destroys the calibration may easily result from such contact.

3. These lamps operate at high temperatures, above the flash point of many organic materials. The environment of the lamp should be kept free of lint and other contaminante, or fires and optical damage to the lamp may result.

4. Lamps must be carefully aligned. Unlighted test lamps are mounted vertically (centered on the optic axis of the detector). The height of the lamp should be checked and adjusted if necessary so that the tip of the evacuation seal coincides with the height of the optic axis. The lamp is then rotated so that the upper press (flat area of lamps) is perpendicular to the vertical plane containing the optic axis. The 50 cm calibration distance is measured from the plane of the detector's surface to the midpoint of the recessed surface of the upper press along a line parallel to the optic axis of the detector.

5. Irradiance measurements should be made only after the lamp has been at its calibration current for approximately ten minutes.

6. The lamp should be turned on and off slowly (i.e. 30 seconds), and great care should be taken so that at no time will the current appreciably exceed the lamp's calibration current.

<u>CALIBRATING AND MAINTAINING DAILY USE STANDARDS</u>

All lamps should be assigned an identifying number which tells whether the lamps is an NBS traceable standard (s) or a daily use unit (d), and the date it was received. In case several lamps are purchased at one time, each number will also carry an identifying letter at the end as shown below:

(From Optronic Labs)	Standard or Daily Use	Date Received	Identifying Letter
NBS Standard	S	9/23/75	A
Daily Use Standard	D	9/23/75	A
	D	9/23/75	B
	D	9/23/75	C
	etc.	etc.	etc.

A calibration control sheet for each lamp will also be maintained showing the lamp's number, where it was purchased and a historical record of its usage. It is important that these control sheets be maintained as Molectron's claim to NBS. Traceability depends on the proper use and maintenance of these standards. For example, after 50 hours of use, the standards which are purchased from Optronic Laboratories lose their calibration's certification and must be replaced.

Calibration of Daily Use Standard

1. Warm up the in-house PR-200 standard, and remove all windows, place on 20 mW/cm^2 range and zero against lamp baffle (do not zero against internal curret zero position or the unknown background radiation will add an error to the lamp output).

2. Place standard lamp in housing and carefully align as described in Item No. 4 on Page 102. Turn lamp power supply on and allow to stabilize for at least ten minutes (note time when lamp is first energized). After stabilization, remove lamp baffle and, if necessary, adjust PR-200 gain to give correct reading in mW/cm^2 as reported on calibration sheet.

3. Remove Optronic Laboratories' lamp and record total time used on its calibration sheet.

4. Install new daily use standard into lamp holder and carefully align. With lamp baffle in place, turn on and allow to stabilize for ten minutes.

5. Rezero PR-200 in the "OPEN" turret position against the lamp baffle.

6. Remove lamp baffle and carefully note PR-200 reading in mW/cm^2. This is the initial calibration of the new daily use lamp. Record this value along with the time used on the lamp's calibration sheet. It is the total irradiance output in mW/cm^2 traceable to Optronic Laboratories' in-house NBS traceable standard.

Routine Check (after ten operating hours) of Daily Use Standards

1. After ten cumulative operating hours, the daily use standard should again be compared to the Optronic Laboratories' in-house standard. The same procedure described in Item No. 1 on Page 103 should be used except before removing the daily use standard and installing the Optronic Laboratories' lamp, a measurement should be made to ensure that the daily use standard's output has not significantly changed during the first ten hours of use. If it has, then the routine checking interval should be shortened or before calibrating, Molectron should age the new lamp by running at 30 VDC for approximately 30 hours.

NOTE: A procedure which could be used to further prolong the life of the Optronic Laboratories' standard would be to initially calibrate several daily use standards at one time, use each of them for ten hours and then recheck all of them at one time.

FINAL IRRADIANCE CALIBRATION OF PR-200 ($watts/cm^2$)

Before the final optical calibration is performed, the probe and instrument have been electrically checked and their gains preadjusted to be close to the final value.

1. Turn on the daily use standard lamp and allow to stabilize for at least ten minutes.

2. Place the PR-200 probe (windowless) into position with the turret open and zero on the 20 mW/cm^2 range against a baffle in front of the lamp.

3. Remove the baffle and allow the lamp's output to fall on the detector surface. Adjust the PR-200 rear panel "CAL. ADJ" control so that the PR-200 reading is x 1.064 higher than the calibrated output of the lamp. For example, if the lamp has a calibrated output of 8.00 $\mu W/cm^2$, then the PR-200 should be adjusted to read:

$$8.00 \ /cm^2 \times 1.064 = 8.51 \ /cm^2$$

The PR-200 is now calibrated for use with an Infrasil Quartz Window with peak transmission of 94%. (This is why the calibration value must be multiplied by 0.94 = 1.064 in order to raise the PR-200 gain to correct for the 94% quartz transmission as compared to 100% transmission for the windowless unit.)

4. Place the baffle in front of the lamp, place the PR-200 probe turret into the "ZERO" position, install a quartz window and allow the system to stabilize on the 20 $\mu W/cm^2$ range.

5. After the unit has stabilized, null the display to "ZERO," ±1.0 $\mu W/cm^2$.

6. Place the turret into the "CAL" position and energize the internal LED standard. Record the display reading in $\mu W/cm^2$.

7. From the above measurement of the LED output with the quartz window, calculate the setting for other window materials as shown below:

LED Reading with Quartz Window = XX.X $\mu W/cm^2$ (measured)

Setting for:	Windowless	= {XX.X mW/cm^2}	x 0.94
	Sapphire	= { " " }	x 1.01
	Irtran-2	= { " " }	x 1.31
	KRS-5	= { " " }	x 1.34

These are the values which should be typed on the PR-200 probe's label.

RADIANT FLUX CALIBRATION (WATTS)

Because the effective detector area may not be exactly 0.2 cm^2, it is necessary to adjust the divide-by-5 $watts/cm^2$ watts conversion to compensate for any area differences.

After the PR-200 has been calibrated against the standard of irradiance (in the watts/cm^2 position), place the PR-200 probe in the beam of a laser with known output. With the PR-200 in the "watts" position, adjust the watts/cm^2-watts trim-pot so the PR-200 gives the proper reading.

APPENDIX C

Correction Factors for Pyranometers with Shadow Bands

The only information obtained on this topic was supplied by Eppley Laboratories. This is reprinted here essentially as provided to us.

INSTRUCTIONS FOR THE INSTALLATION AND OPERATION OF THE EPPLEY SHADOW BAND STAND FOR THE MEASUREMENT OF DIFFUSE SKY RADIATION

1. <u>General</u>

This shadow band stand has been designed for use with the 180° Eppley Pyranometer. Two models are available: (a) for exposure in the latitude range 0-60°N or S and (b) for exposure in the latitude range 60-90° N or S. The appropriate method for correcting for the portion of sky screened by the shadow band and for evaluation of measurements of diffuse sky radiation has been published elsewhere[1-3]. However, for convenience, tabular values of the shadow band corrective factor, applicable to average conditions of partly cloudy skies, are given in this leaflet.

2. <u>Exposure</u>

The shadow band stand should be mounted on a suitable platform in the desired location. The latter is not supplied but can easily be constructed of angle metal. In the case of the model intended for use in middle and low latitudes, provision must be made to permit movement of the radiometer vertically. For both models, the width (i.e., the E-W axis) of the main supporting stand must not exceed 21 inches: for the 60-90° model, the size of this stand must be chosen so that the shadow band setting for the latitude in which the shadow band instrumentation is to be operated is not restricted over the whole range of solar declination.

The main supporting stand must be of rigid construction, especially in regions where high winds are experienced.

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1. Drummond, A. J., 1956: "On the measurement of sky radiation," Arch. Met. Geoph. Biokl., Series B, 7, 413-436.
2. IGY Instruction Manual, 1958, Vol. V, Pt. VI, "Radiation Instruments and Measurements." London, Pergamon Press, 426-429.
3. Drummond, A. J., 1964: "Comments on <u>Sky radiation measurement and corrections</u>," J. Appl. Meteor., 3, 810-811.

The supporting stand should be so oriented that the main axis is as nearly N-S as possible. The other exposure requirements of the shadow band sensor are similar to those for the measurement of total sun and sky radiation.

3. Installation

The shadow band stand should first be placed on the specially constructed supporting stand (not supplied) referred to above. Then it should be verified that the N-S orientation is closely correct and that the base plate is level. The latter should be secured rigidly to the supporting platform with four bolts. It is recommended that slots rather than holes be provided in the supporting platform, to enable a small adjustment to be made for the N-S orientation, if necessary (this is most easily accomplished through visual observations of the symmetry of the shadow at or near sunrise, noon and sunset).

Next, the two wing nuts clamping the side bars carrying the shadow band should be loosened and each bar reset so that the 0° mark of the declination scale engraved on the bar is opposite the index engraved on the plate with the latitude scale. Both wing nuts should then be tightened.

The bolts clamping the latitude adjustment (0-60° or 60-90°) should be loosened and the appropriate latitude setting selected. These bolts should then be tightened--no further adjustment in this plane is required unless the shadow band stand is removed to another latitude.

The pyranometer should be placed on the small adjustable platform and secured. The height of this platform should be set (with the aid of the locking screw on the collar) so that the receiver of the radiation sensor is approximately in the center of the shadow band. Then the two bolts securing the horizontal bars of the stand should be loosened and the bars moved until the receiver of the sensor, as viewed through the two small holes drilled in the band, lies in the vertical plane determined by the positions of these holes. In order to obviate skewness in this setting both bars carry similar relative scales graduated from a common reference mark. Such a provision is also made for the latitude and declination settings. The exact height adjustment of the sensor should be effected (this is also easily done by viewing the receiver surface through the sighting holes) and the screw on the collar tightened--no further adjustment, in this connection, is necessary unless the instrument location is changed. Finally, it should be verified that the radiation sensor is properly levelled (i.e., check of spirit level on instrument).

4. Operation

The shadow band will require resetting along the polar axis in accordance with the changing solar declination. Generally, the shadow cast on the radiometer should be checked daily when the sun is unobscured by clouds. However, the position of the band can be adjusted in the absence of sunlight by reference to the graduated declination scale.

5. Evaluation of records

In order to evaluate the assembled records of diffuse radiation it is necessary to correct the measured values for the fraction of the radiation which is screened by the shadow band. In the following table, the theoretically derived values for the 16th of each calendar month are presented. A small correction (4 percent) is included to relate isotropic to real sky conditions. Multiplication of the basic measurements by the tabulated factors will yield the desired evaluations of diffuse sky radiation with sufficient accuracy for most practical purposes (±2 percent).

Shadow band corrective factors for average partly cloudy skies

Lat °N	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Lat °S	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June
0	1.17	1.21	1.24	1.22	1.19	1.16	1.17	1.20	1.23	1.21	1.19	1.16
10	1.15	1.19	1.23	1.23	1.20	1.18	1.19	1.21	1.23	1.20	1.16	1.14
20	1.13	1.16	1.21	1.23	1.21	1.19	1.20	1.21	1.22	1.18	1.14	1.12
30	1.11	1.14	1.19	1.22	1.21	1.20	1.21	1.21	1.20	1.15	1.12	1.10
40	1.09	1.12	1.17	1.20	1.21	1.20	1.21	1.21	1.18	1.13	1.10	1.08
50	1.07	1.10	1.14	1.18	1.20	1.20	1.20	1.19	1.15	1.11	1.08	1.06
60	1.05	1.07	1.11	1.15	1.19	1.20	1.19	1.17	1.13	1.09	1.06	1.04
70	-	1.05	1.08	1.13	1.18	1.21	1.19	1.14	1.11	1.06	1.04	-
80	-	-	1.06	1.11	1.19	1.22	1.20	1.14	1.09	1.04	-	-
90	-	-	1.05	1.11	1.20	1.23	1.21	1.15	1.07	-	-	-

The Eppley Laboratory, Inc.
Newport, Rhode Island
October 1966

APPENDIX D

Calibration of Longwave Radiometers

Description of the Instruments

Longwave radiometers for the purposes of this report are those instruments which respond to radiation as long as 40 micrometers. There are a large variety of such instruments in use in various technologies, however, for the purposes of this report we are concerned only with the simple broad spectrum thermal instruments described in the following paragraphs.

Longwave radiometers respond to radiation from about 0.3 to about 40 micrometers. They are designed so that the response is uniform across that spectral range. These instruments are commonly available in two forms, unidirectional instruments and net radiometers.

The unidirectional instruments have a geometric response like that of a pyranometer (proportional to the cosine of the angle from normal to surface). They are commonly constructed in a similar fashion. The dome is made of polyethylene, or sometimes absent altogether in order to assure transmission of longwave energy. Those without domes have a curtain of air to isolate the surface of the sensor from the environment. In the unidirectional instrument the bottom or reference side of the thermopile is maintained at atmospheric temperature, or some other temperature which is precisely monitored.

The net radiometer is an instrument which measures the "net" radiant flux through an imaginary window in the plane of the instrument. Instead of having a reference side, the instrument has two surfaces one on each side of the thermopile. The reference is essentially the radiation falling on the opposite surface. A more complete description of these instruments is given by Fritschen.*

*Leo J. Fritschen, "Construction and Evaluation of a Miniature Net Radiometer," Journal of Applied Meterology, Vol. 2, No. 1, Feb. 1963, pp. 165-172.

Calibration

The calibration of longwave radiometers is the measurement of the instruments' output when the instrument is subjected to known conditions. These known conditions should include those conditions which are to be measured by the instrument. The variety of conditions to which the instrument is subjected in the laboratory should be representative of those which are important during the use of the instrument for measurement. Depending on the use of the radiometer described here all of the tests discussed for pyranometers could be appropriate. In addition, it is important to know the effective temperature of the environment as seen by the instrument. This is because the earth and the environment itself including the gasses and particles within the earth's atmosphere radiate energy at wavelengths to which these instruments are sensitive. Thus, any calibration chamber for these instruments must have the temperature of all surfaces which are seen by the instrument carefully controlled.

The theory and use of such a chamber is discussed by Fritschen (see reference). A description of a typical facility is given by Siemen Ersking in the following pages.

CALIBRATION METHODS:
SIEMEN ERSKING
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DESCRIPTION OF CALIBRATION CHAMBER AND CALIBRATION METHOD

The net radiometers are calibrated in a modified version of the calibration chamber described by Leo J. Fritschen: Construction and Evaluation of Miniature Net Radiometer. Journal of Applied Meteorology 2, 165-172, 1963. (See Figure D1). The top, the bottom and the two sides of the chamber are lined with 1 mm brass plates. The inside of the chamber is painted with Parsons' optical black lacquer. On the outside of the plates are soldered 10 x 12 mm copper tubes formed as a spiral. Water can independently be pumped through the tubes of the upper and the lower half of the chamber.

A long-wave radiation flux is obtained having different temperatures in the two sections. The temperature difference is kept constant by thermostats and measured by use of thermoelements. The net long-wave radiation flux is calculated from the temperature differences and the emissivity of the chamber.

A short-wave radiation flux is obtained from a halogen lamp. Long-wave radiation from the lamp is filtered by passing four layers of glasses placed outside the chamber.

The temperatures in the two sections are kept equal at 20°C and the light intensity kept constant by a voltage stabilizer. The radiant flux density is varied between 0,3 and 1 cal cm^{-2} min by inserting sheets of metal nets between the lamp and the long-wave radiation filters. A Kipp and Zonen pyranometer, located in the same position as the net radiometer, is used as a standard reference. The pyranometer calibration factor is verified at the World Radiation Center, Davos.

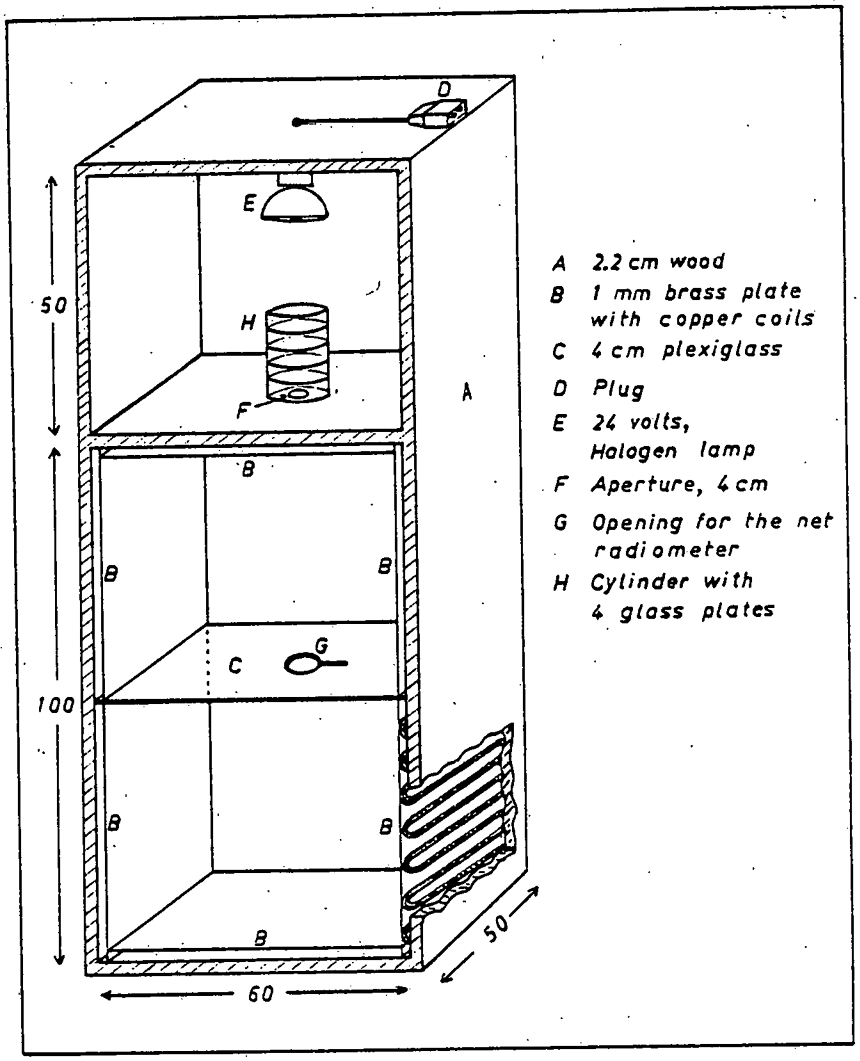

Figure D1. Net Radiometer Calibration Cahmber Schematic Design.