An Integrating Pyranometer for Climatological Observer Stations and Mesoscale Networks

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ABSTRACT

The silicon photovoltaic solar cell has made possible the construction of simple pyranometers of reasonable accuracy. Cell response is linear, temperature sensitivity is low, and spectral response does not cause serious error, provided the cell is used in open sunlight.

The solar cell has been mounted beneath a special diffusing unit to obtain a rugged pyranometer with excellent cosine response. This pyranometer has been coupled with a solid state integrator developed for this purpose. The integral is recorded with either visual or printing counters.

Tests were made during September 1965 through February 1966 when low solar altitude and severe operating conditions would cause greatest error; and again during March 1966 through July 1966 when solar radiation intensities were high. For the first period the standard error of estimate and the solar radiation means were, respectively, 84 and 2200 Wh m^{-2} day^{-1}. For the second period the corresponding values were 158 and 5630 Wh m^{-2} day^{-1}.

1. Introduction

The global radiation received at the earth's surface is the primary energy source for many meteorological, agricultural and hydrological processes. At a given site it varies considerably with changing atmospheric conditions, time of day, season and aspect, but remains largely independent of other surface characteristics. Consequently, there is a need to measure such a fundamental climatic parameter routinely. The most meaningful measurement for this work is the energy flux density of the global radiation, passing through a horizontal plane of unit area, integrated over periods of an hour, day or longer. Previously, these measurements have been limited by the high cost of reducing data, high initial equipment costs, and the lack of rugged, reliable instruments suited to field observer operation with minimal maintenance.

This paper describes an instrument which has been designed to overcome most of the above limitations, by mounting a silicon solar cell beneath a special diffusing unit to obtain a rugged pyranometer with excellent cosine response. This pyranometer has been coupled with a solid state current integrator developed to provide the radiation integral registered in digital form on either a visual or printing counter.

2. Literature review

Trickett *et al.* (1957), Morikofer *et al.* (1957), and Robinson (1966) have discussed many of the pyranometers in use, all of which are based on one or another of the following three principles: the thermal response of a suitable receiving surface such as a bimetallic strip or hot junction of a thermopile; the response of a photoelectric cell; and photochemical methods.

Two versions of the thermopile pyranometer are in common use today. The Kipp (Moll-Gorcznski) solarimeter is used in Europe and the Eppley pyranometer (180° pyrheliometer) is used primarily in the United States. Robinson (1966) has critically discussed the merits of both pyranometers. These are fairly reliable instruments of sufficient accuracy for use at first order weather stations; however, they require continual attention by trained observers. The output is frequently recorded on a strip chart, necessitating considerable time and expense in chart reading. Accurate integration by chart reading is particularly difficult on partly cloudy days, and recorders with ball and disk integrators are recommended. A capital outlay of approximately $1000 is required for Eppley or Kipp integrating systems. The costs and required observer skills mitigate against the use of the Eppley and Kipp pyranometers for routine measurements. In this study a dc amplifier coupled with an electronic integrator (Thurtell and Tanner, 1964) and digital printout counter has been used to integrate the Eppley output.

The use of silicon photovoltaic cells to measure solar radiation was first discussed by MacDonald.[1]

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[1] MacDonald, T. H., 1960: The solar cell as a pyranometer receiver. Paper presented at the Fall Instrumentation-Automation Conference, Instrument Society of America, New York, 26–30 September.

Schoffer *et al.*[2] found a satisfactory comparison between a solar cell and an Eppley pyranometer on five days in December. They also showed that the cell could be biased to allow an increased load resistance while maintaining linearity of response. Yellott *et al.*[3] have commercially produced a temperature-compensated solar cell pyranometer. Their "Sol-a-meter" has a voltage output comparable to a 50-junction Eppley instrument and requires a 10-mV potentiometer recorder.

Federer and Tanner (1965) used a commercial mercury coulometer and a small solar cell biased by a larger cell, and found that daily solar radiation flux density could be predicted with an accuracy of ±200 Wh m^{-2} day^{-1} (±18 ly day^{-1}). Further experience has shown the Curtis coulometers to be inconvenient for routine field use and their reliability in the biased solar cell circuit is inadequate for routine climate measurements.

Whillier (1964) integrated the current output of unbiased solar cells by connecting them directly into a commerical dc ampere-hour meter. This instrument which is available commercially does not require outside power supplies and its cost is moderate. The Whillier pyranometer measured solar radiation to an accuracy of ±4% at high intensities, but its failure to register at intensities below 140 W m^{-2} (0.2 ly min^{-1}) would be serious under winter conditions in temperate latitudes. Also, error is further increased by the poor cosine response of the bare cell at low sun elevation angles. Spencer (1963) also has constructed a light integrator using the output voltage of a large number of solar cells and an RC integrating circuit.

3. Pyranometer

A silicon solar cell can be operated as a photodiode, in which the short-circuit current is directly proportional to the incident solar radiation. Suitable current integrators can then provide total energy flux density for any desired time period from a few minutes up to several days.

Several characteristics of silicon solar cells are attractive for measuring global radiation, whereas others appear to detract from their use. These characteristics are discussed with respect to the potential of the cells as pyranometers.

a. Advantages of the silicon solar cell. The cells have a high short-circuit current output, typically of 20–25 mA cm^{-2} active surface area under a solar radiation intensity of 1000 W m^{-2}. They are superior to selenium photovoltaic cells in that they do not exhibit fatigue when exposed to fluctuating light conditions and they have a response time in the order of 10 μ sec. Silicon solar cells have very low dark currents when operated in the reverse-biased mode to allow an increase of load resistance while maintaining linearity of response. The cells are stable under prolonged exposure to a wide range of weather conditions, are inexpensive, and can easily be mounted to receive solar radiation.

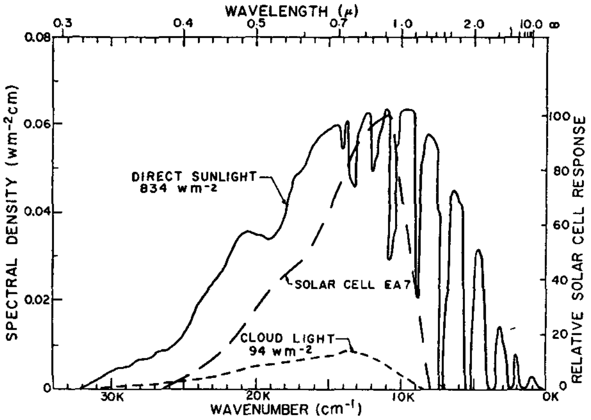

FIG. 1. Spectral distribution of solar radiation at sea level for a clear day [after Gates (1965)], of sunlight from a complete overcast day [after Albrecht (1935)], and the spectral response of the EA7 silicon cell.

b. Spectral response. The relative spectral response of the solar cell does not extend uniformly over the full solar radiation range. A typical response curve is presented in Fig. 1. Changes in the spectral distribution of the incident radiation, coupled with the non-uniform spectral response of the cell, can cause errors in the cell output. Albrecht's (1935) measurements illustrate that the major change in spectral distribution of solar radiation occurs in the near infrared where water vapor absorption takes place on cloudy days.

The area under the spectral distribution curves presented in Fig. 1 is directly proportional to the energy received by a horizontal surface. Energy received on a completely overcast day is estimated from Fig. 1 to be 11.3% of that received on a clear day. When both clear and cloudy day spectral distributions are weighted according to a typical response curve of a solar cell (EA7), the response on a cloudy day is 12.6%. Therefore, errors incurred under different sky conditions, due to the spectral response of the cell, will be small. The field tests of Federer and Tanner (1965) confirm this conclusion, as do those in this paper.

c. Electrical characteristics. In this pyranometer, we used EA7 silicon solar cells[4] which have a maximum dark current of less than 1 μA at room temperature.

In the integrator which we have developed, the solar cell operates in series with a transistor emitter and so does not have a linear resistive load.

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[2] Schoffer, P., P. Kuhn and C. M. Sapsford, 1961: Instrumentation for solar radiation measurements. Paper presented at the United Nations Conference on New Sources of Solar Energy, 15 May.

[3] Yellott, J. I., L. Chamness and K. Selcuk, 1962: Silicon cells for pyrheliometers and pyranometers. Paper presented at the Winter Meeting of the American Society of Mechanical Engineers, New York, 25–30 November.

[4] Hoffman Electronics Corporation, El Monte, Calif. (EA7E1 cells mounted with leads but without glass encapsulation and with epoxy covering).

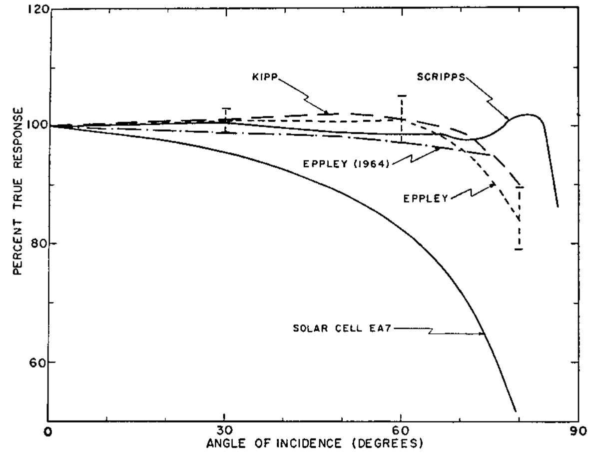

FIG. 2. Comparison of the cosine response of the Scripps head with the bare solar cell and the Eppley and Kipp pyranometers.

Estimates of the temperature coefficients (TC) of the short-circuit current of the silicon solar cells vary from $+0.0004$ C^{-1} (Federer and Tanner, 1965) to $+0.0010\pm0.0001$ C^{-1} (Selcuk and Yellott, 1962), when measured in sunlight. The TC of the short-circuit current is positive in the 0.85 to 1.2 μ region, but is slightly negative or zero for wavelengths less than 0.85 μ. Temperature compensation does not seem necessary since, if the pyranometer is calibrated at 20C, a TC of $+0.001$ C^{-1} introduces only 2% error at 0 and at 40C.

d. Cosine response. For most meteorological, agricultural and hydrological studies, we want to know the vertical energy flux density through a horizontal plane. A correction can then be applied to obtain the flux received either by a horizontal or a sloping surface. The flux through horizontal plane has to be measured with a flat sensor which obeys Lambert's cosine law.

A typical cosine response curve for a bare solar cell is presented in Fig. 2. We have considerably improved the Lambert's law response of the bare solar cell by placing it beneath a specially designed diffuser. This is a modification of a unit used by the Scripps Institute of Oceanography (Austin, 1964), which in turn is an adaptation of a unit used by Boyd (1951). Foster (1951), Pleijel and Longmore (1952), and Weston and Paix (1960) have all used designs based on similar principles.

The cosine-corrected head is shown in Fig. 3. The diffusing disk is made from acrylic plastic[5] and is thick enough to prevent any preferential scattering of the transmitted light in the forward direction, parallel to the incident beam. The 0.525-inch thick disk will transmit approximately 15% of the incident light. The spectral transmittance is uniform between 0.4 and 1.1 μ which are the approximate cut-off points for the silicon cell.

The body of the cosine-corrected head was constructed by machining an aluminum model which was used to make a silicone rubber mold.[6] The final product was cast of epoxy.[7]

The acrylic plastic and the epoxy are easily machined. Reflection from the machined epoxy surfaces, which turn gray upon cutting, can be reduced by spraying with black paint.[8] The diffuser was cemented in place with Dow Corning Glass and Ceramic Adhesive which prevents water entering the solar cell cavity from above. Drainage from the head is provided by a small radial channel leading to an outlet hole. The head is mounted on an aluminum plate with three screws 120° apart.

The solar cell was mounted on a threaded bakelite stem and the electrical leads passed through the stem, clamped firmly at the base and taken to the integrator. The pyranometer can be set up tens of feet from the integrator.

This head improves the cosine response because, at low sun angles, the exposed vertical edge of diffusing plastic enables more light to reach the cell, thereby offsetting losses due to the increased reflectance from the top horizontal surface. Eventually, a sun angle is reached when the compensation is too great. However, this can be controlled by placing the outside rim to cut off light at very high angles of incidence. Therefore, the height of the exposed edge of the diffusing plastic

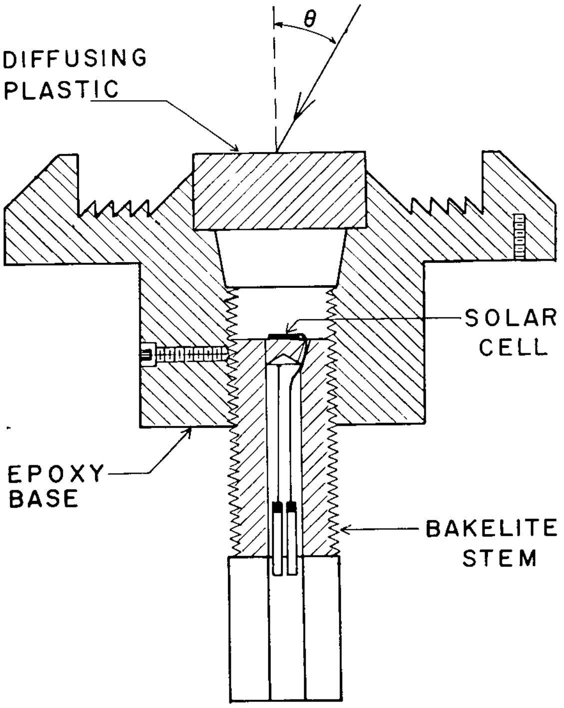

FIG. 3. The cosine-corrected head.

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[5] Rohm and Haas, Philadelphia, Pa., Plastic W# 2447.

[6] Dow Chemical Co., Midland, Mich., Dow Corning Silastic RTV589.

[7] Emerson and Cuming, Inc., Canton, Mass., Stycast 2651MM.

[8] Minnesota Mining and Manufacturing Co., St. Paul, Minn., 3M Velvet.

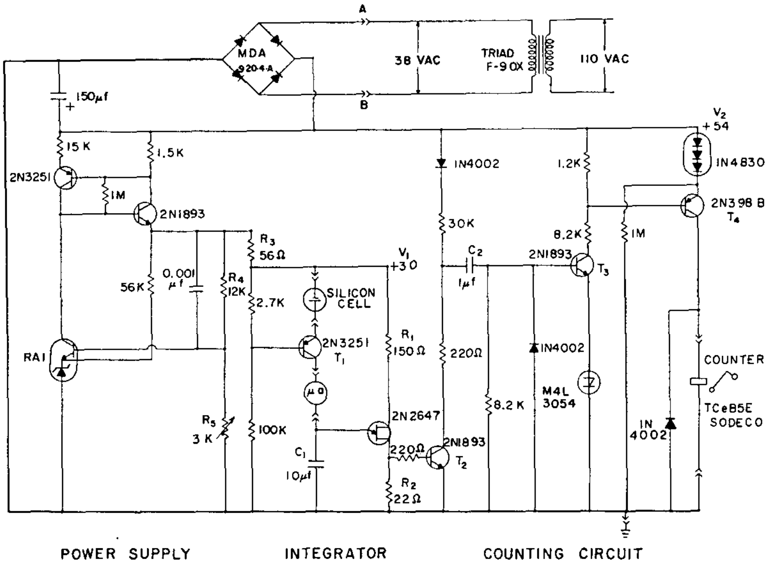

FIG. 4. Circuit diagram of the power supply, integrating, and counting circuits.

and the distance between the edge of the diffuser and the outside rim are the two critical design parameters. We obtained best results for this particular diffusing plastic with an exposed edge of 0.125 inch and a diffuser rim distance of 0.8 inch, but variations of ±0.05 inch in the latter parameter did not significantly change the cosine response. The 45° ridges at the bottom of the head eliminate reflections from the base onto the exposed edge.

Global radiation $K\downarrow(\theta)$ incident on the pyranometer is the sum of the direct beam component $I\cos\theta$ and the diffuse sky radiation D. This gives the equation

$$K\downarrow(\theta)=D+I\cos\theta. \tag{1}$$

Cosine response measurements were made in a darkroom with the pyranometer mounted on a goniometer platform and illuminated with a 1000-W projector focused at infinity. Under this arrangement, D approaches zero, I is the light intensity when $\theta=0$, and $K\downarrow(\theta)$ is the light incident on the pyranometer at each value of θ. The corresponding pyranometer response can be represented by $R(\theta)$. For each value of θ, the agreement with the cosine law was determined as,

$$\text{True response (per cent)}=\left[\frac{R(\theta)}{R(0)\cos\theta}\right]100, \tag{2}$$

where $R(0)$ is the pyranometer response for $\theta=0$.

Data obtained for a bare solar cell and a solar cell beneath the cosine-corrected head are presented in Fig. 2. The Eppley (1964) curve was plotted from data in the Eppley Bulletin,[9] and the Kipp solarimeter data is reproduced from Robinson (1966). The mean Eppley curve was drawn from results of studies by Woertz and Hand (1941), MacDonald (1951), Dogniaux and Pastiels (1955), and Fuquay and Buettner (1957). Maximum and minimum values given in the literature are shown for $\theta=30°$, 60° and 80°.

The cosine-corrected head is within ±2% of the true cosine response, until θ exceeds 84°. Estimates for a clear day in mid-December at Madison, Wis. (43N), assuming $D=0$, show that the cosine-corrected head underestimates the total daily solar radiation by 2% and the Eppley by 7%. These errors are decreased as the sun incident angle decreases toward summer and as D/I increases, particularly on overcast days, and near sunrise and sunset when air mass values are high.

e. Sensitivity adjustment. The output of the solar cell under a cosine-corrected head can be varied by adjusting the distance of the cell from the diffuser. When a cell position is changed from 1.5 mm below the diffuser to 25 mm below, the current output of the cell is approximately halved. The current output is approximately a linear function of distance below the diffuser. The cells have been generally set 6–12 mm behind the diffuser for studies to date.

4. Integrator

The operation and temperature coefficient of the integrator circuit, and the fabrication of the integrating unit, are discussed in this section. Modifications are suggested which enable the use of portable power supplies and/or print-out counters with the integrator.

a. Operation of circuit. The circuit, comprising a regulated power supply, integrator and counting circuit is shown in Fig. 4. In this configuration, the solar cell is in series with the transistor emitter and acts as a photodiode in which the current through the cell is directly proportional to the incident light. This current

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[9] Eppley Laboratory, Inc., Newport, R. I., Bulletin No. 4, 1964.

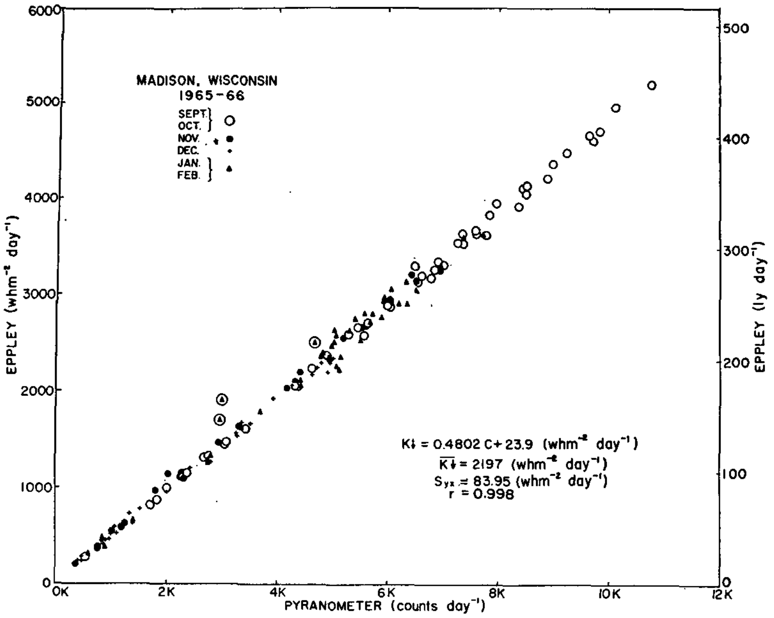

FIG. 5. Integrating pyranometer reading vs. daily solar radiation measured with an Eppley pyranometer, 12 September 1965 through 15 February 1966.

is used to charge the capacitor C_1[10]. The capacitor C_1 and the unijunction transistor operate as a relaxation oscillator. The unijunction transistor offers a very high impedance until its base voltage reaches a given level, at which it switches to a conducting state, discharging C_1. As capacitor C_1 is discharged, transistor T_2 is turned on thereby discharging capacitor C_2. When the unijunction transistor returns to the non-conducting state after discharging C_1, transistor T_2 becomes non-conducting. Capacitor C_2 is then recharged and both transistors T_3 and T_4 conduct, so that a single count is recorded on the electromagnetic counter. The cycle is then repeated.

The unijunction transistor discharges C_1 when its base voltage exceeds ηV_1, where η is the unijunction intrinsic stand-off ratio. The value of η is typically 0.75 for the 2N2647 unijunction transistor. Therefore, the accuracy of the integrating circuit is largely determined by the accuracy with which the voltage supply V_1 is regulated. Voltage regulation is obtained by using a RA1 silicon reference amplifier transistor. Line voltage variations from 95 to 120V ac cause V_1 to change less than 0.3%. Currents up to 8 mA can be drawn by the integrating circuit without changing V_1. The TIS43 unijunction transistor can be substituted for the 2N2647 unijunction transistor.

Temperature dependence of V_1 is minimized by using wire-wound elements with low temperature coefficients for R_4 and R_5. Resistors R_1 and R_2 are selected to maximize the temperature stability of the unijunction transistor triggering voltage.

b. Fabrication. The circuit components have been mounted on a printed circuit board which can be put in a small 7×12×6 inch cabinet, with the transformer, heater, two electromagnetic counters and a 48-hr timer. A microammeter calibrated in W m^{-2} can be included to provide an instantaneous measurement of the energy flux density. The use of two counters and a timer which operates a switch every 24 hr, enables each successive day's record to be registered on a different counter. Consequently, one day's record can be read by the observer at any time during the following day. Panel lights are used to identify the operating counter on a particular day. The timer is set to switch at midnight but variations in switching time up to ±2 hr will not affect the results. Our experience indicates that reading errors will be reduced if the counters are mounted so that the observer can only read the correct counter each day. This could be done by mounting the timer and counters in a configuration so that at the observation time one counter can be completely covered by a plate mounted on the timer hand. Alternatively, the counters could be recessed so that they can be read only when lit by specially mounted panel lights.

c. Temperature coefficient. The overall temperature coefficient of the unit was measured by placing the complete integrator in a temperature chamber and replacing the solar cell with a constant current source. The temperature coefficient was found to be +0.00068 C^{-1}. This means that the cabinet temperature can fall to −20C without incurring errors larger than 3% for an instrument calibrated at 20C. A thermostat and 40-W heater are included in the cabinet to keep the temperature above 2C and prevent condensation.

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[10] Metallized Mylar Capacitor, No. 31-106C, Texas Capacitor Company, Houston, Tex.

d. Modifications. Frequently, measurements must be made where a 110-V supply is not available. Under these conditions, this circuit could be operated by a 12-V car battery and a low cost inverter. Frequency regulation to ±3 Hz is satisfactory for the electronics but better regulation may be required for the timer unless frequent timer adjustment is made.

This circuit can be modified to operate a printing counter with little extra cost by using the 2N398B transistor to drive another transistor as a final stage in the counting circuit. An appropriate counter power supply is necessary.

5. Results

The integrating pyranometer was compared with an Eppley pyranometer for a 5-month period from 12 September 1965 through 15 February 1966, and for a 4-month period from 27 March 1966 through 31 July 1966. The tests were made at Madison on top of a University building where there was an unobstructed horizon. Results are presented in Figs. 5 and 6 for the two periods. The sensitivity of the pyranometer was changed between these two periods.

Analysis of the data collected between 12 September 1965 and 15 February 1966 shows the standard error to be 84 Wh m^{-2} day^{-1}, with a mean radiation intensity of 2200 Wh m^{-2} day^{-1}. This is an error of ±3.8% assuming all error is in the integrating pyranometer. For the period 27 March 1966 through 31 July 1966, the standard error was 158 Wh m^{-2} day^{-1}, with a mean radiation intensity of 5630 Wh m^{-2} day^{-1}, representing an error of ±2.8%.

Generally, there was sufficient wind to keep the surface of the cosine-corrected head free of snow, but it is necessary to inspect the head each day and to clean it as required. Snow fell continually on the three days which have been circled in Fig. 5 and apparently remained on the head, thereby decreasing the integrating pyranometer record. Snow accumulation, dust and dirt on the head will introduce errors.

The cosine and spectral response errors of the pyranometer have been discussed. These errors are not additive because on cloudy days when the error due to the spectral response is greatest, the increased scattering due to the clouds will tend to reduce the cosine response error. The combined errors would probably not exceed 2%.

During the tests the temperature of the integrator cabinet was controlled between 0 and 30C; thus, maximum temperature errors for an instrument calibrated at 20C would be 1.4%. The temperature fluctuations of the solar cell were not monitored; however, the head was mounted so that the solar cell temperature is close to the ambient air temperature. Noon air temperatures for the period ranged between +30 and −25C. This introduces a maximum error of −4.5% for an instrument calibrated at 20C and assuming a solar cell TC of 0.001 C^{-1}. Low temperatures are associated with low solar radiation intensities, which means that the absolute magnitude of the error at −25C may be much less than the absolute magnitude of the error at some higher temperature.

In general, all the errors, when expressed as percentages, are greatest under low radiation conditions and, therefore, the absolute magnitude of the error will be quite small.

Finally, the Eppley pyranometer has been used as a standard. The Eppley cosine response is poorer than

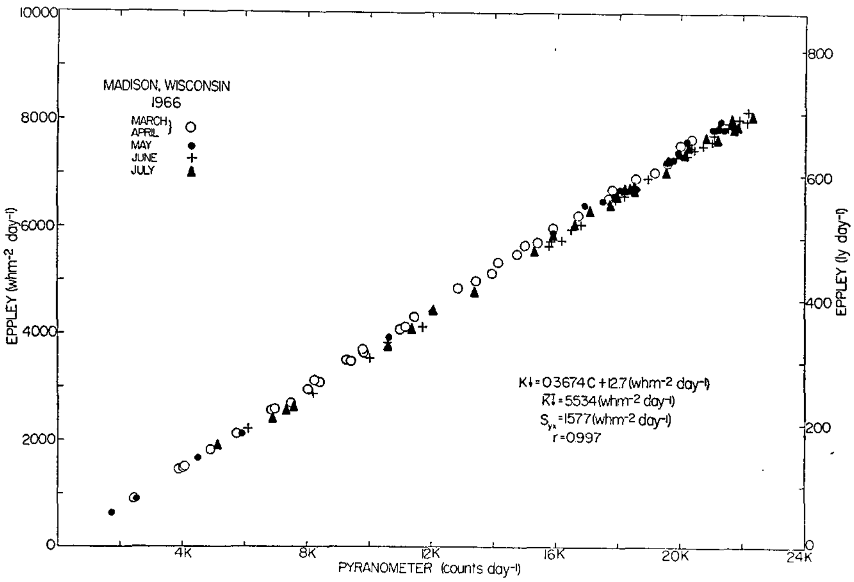

FIG. 6. Integrating pyranometer reading vs. daily solar radiation measured with an Eppley pyranometer, 27 March 1966 through 31 July 1966.

the cosine-corrected head but it has a uniform spectral response. The Eppley has a TC of -0.001 to -0.003 C^{-1} (Drummond *et al.*, 1965) compared with the positive TC of the solar cell. No compensation has been made for these errors.

Nicolet (1948) indicates that an accuracy within ±5% can be achieved in short-term, integrated totals of global radiation measured on a continuous basis. The agreement we found seems to be about that which Nicolet indicates for careful, continuous observations, so that records from the integrating solar cell pyranometer will not be appreciably less accurate than from a standard Eppley network. The improvement gained by closer spacial sampling through a region will offset any degradation of record at any one site.

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