Development of a new controller for absolute cavity, cavity calibration, and solar irradiance measurement

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Abstract

This document discusses the development of a fully automatic controller for an absolute cavity radiometer. It describes using the controller to measure the AHF Eppley cavity radiometer, but the controller can be reconfigured for any absolute cavity radiometer. The AHF Eppley cavity radiometer measures solar irradiance and is self calibrating.

The main component of the controller is Campbell Scientific's CR6 datalogger, which has some unique features. The resolution and accuracy of the CR6 voltage measurement easily satisfy the WMO classifications for a pyrheliometer used as a standard reference. The computer program can be developed to make manual, semiautomatic or fully automatic measurements on a given time interval with minimum input required from the user.

Introduction

Direct Normal Irradiance (DNI) is the solar radiation arriving at the Earth's surface directly from the sun on a surface held normal to the rays that come in a straight line from the sun at its current position in the sky. This parameter is of utmost importance to the solar energy industry. For several decades, the sun's output at the top of earth's atmosphere has been measured by a variety of space based radiometer. DNI measured on the earth's surface is smaller than that measured at the top of the atmosphere due to scattering and absorption. The value varies because of varying distance between the earth and sun, and because of changes in the earth's atmosphere. It is a difficult parameter to measure and one of the most expensive measurements in the field of broadband solar and infrared radiation measurements. It requires a solar tracker, which is expensive to use.

The most accurate pyrheliometers are electrically self-calibrating absolute cavity radiometers (ACRs). A resolution of 100 nV or better on the measurement of the thermopile voltage allows equivalent in radiation of approximately 0.1 W/m^2. The sensitivity needs to be ~2.0 W/m^2 for it to be classified as a standard pyrheliometer.[b] The measurement of DNI cannot be made from the first principles of physics.[a, b]

Absolute cavity radiometer model HF manufactured by The Eppley Laboratory, has been a reference standard level device since 1978. The sensor consists of a balanced pair of cavity receivers attached to a wire-wound thermopile. The blackened cavity receivers are also fitted with electric heater windings. These heaters allow for absolute operation using the electrical substitution method relating the radiant power to electrical power in SI units. See Eppley cavity manual for details of construction and operation of these cavities.[c, d]

The Eppley HF radiometer element with baffle tube and blackbody are fitted into an outer tube that acts as the enclosure of the instrument. Model AHF is fitted with a shutter attached to the outer tube. Figure 1 shows a schematic of the cavity.

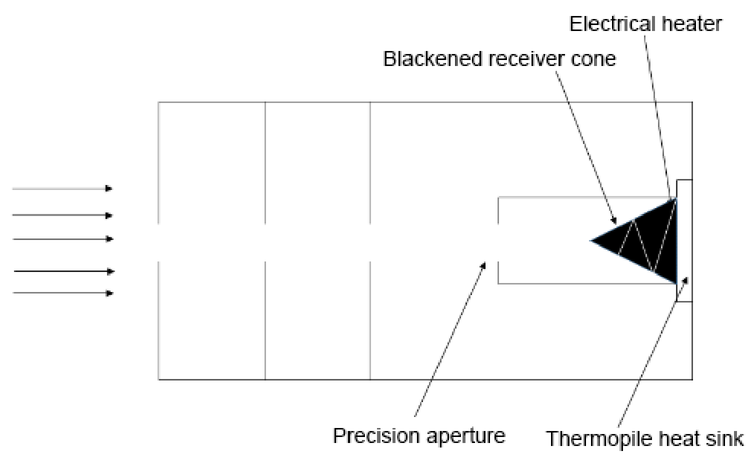

Figure 1. Schematic of a absolute cavity radiometer.

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[a]Kinsell L. Coulson, *Solar and Terrestrial Radiation*, Academic Press (1975).

[b]Frank Vignolla, Joseph Michalsky and Thomas Stoel, *Solar and Infrared Radiation Measurements*, CRC Press (2012).

[c]J. R. Hickey, *Solar Radiation Measuring Instruments: Terrestrial And Extra-Terrestrial*, Proc. SPIE 0068, Optical in Solar Energy Utilization I, 53 (1976).

[d]Instruction manual for *AHF Self-Calibrating Cavity Pyroheliometer serial number 28560*.

A control unit measures the required parameters from the cavity radiometer. The control unit provides the calibration heater power setting, turns on the heater, selects the signals to be measured, and activates of the shutter. The signals measured are the thermopile voltage, heater voltage and the heater current, body and the tube temperatures. The heater current is measured as the voltage drop across a 10 Ω precision resistor. The instrument temperature is measured using internally mounted thermistors. This document describes the development of a control unit that allows for computer control of shuttering, calibration heater and measurement functions. The calculations operations are also performed within a MPU in our controller and data is stored for further use.

Instrumentation

The heart of the controller is a Campbell Scientific CR6, a field-deployable datalogger with a built in MPU. Campbell Scientific is well known in industry for rugged dataloggers with quality measurements. Detailed specifications are available at Campbell's website.[e]

The WMO-based classifications of a standard pyrheliometer requires a resolution of 0.51 W/m^2. To achieve this, the accuracy for the thermopile voltage measurement needs to be ~0.58 µV. The measurement resolution of the CR6 is 50 nV to 100 nV, depending on the mode of operation and value of notch frequency used. The measurement accuracy is limited by the measurement offset, which is 2 µV for differential measurements using input reversal. However, in the actual measurement, the offset is first measured and then subtracted from the subsequent solar irradiance measurement. This process is repeated every 20 to 30 minutes. Thus the only limitation on our accuracy should be ~0.4 µV (0.04% of the range), which provides an accuracy of 0.4 W/m^2 for the solar irradiance measurements. The accuracy easily satisfies the WMO classification requirement for a standard pyrheliometer. Table 1 compares the CR6 accuracy with the accuracy of the NI 4065 and Agilent 34970 A/ 34972, the two most commonly used controllers in the field. These accuracies are for the 100 mV range, which is the best case scenario.

Agilent 34970 A	NI 4065	CR6
3.53 µV	3.03 µV	2.6 µV

TABLE 1: Datalogger accuracies for 100 mV range.

The specification for the Agilent and NI are valid for 24 hour period and for a temperature of 23°C ±1°C, whereas the CR6's specification is for a temperature range of 0° to 40°C. Clearly, the CR6 accuracy is better than the other two dataloggers. Additionally, users can obtain a better accuracy by nullifying the offset irrespective of which system they use. In our controller program, we measure the offset (both logger and sensor) and subtract it from the subsequent measurements. Thus in the actual measurement, our accuracy is better than the one noted above.

Figure 2 shows a block diagram of the controller and Figure 3 shows a circuit diagram of the controller. The radiometer is an absolute cavity that is calibrated against the world primary maintained at WRR, Davos. The calibration is done every five years. WRR provides a calibration time sequence, the measurement, and the data format to be submitted. The cavity and controller combination form a complete unit and are traced back to WRR for calibration purposes.

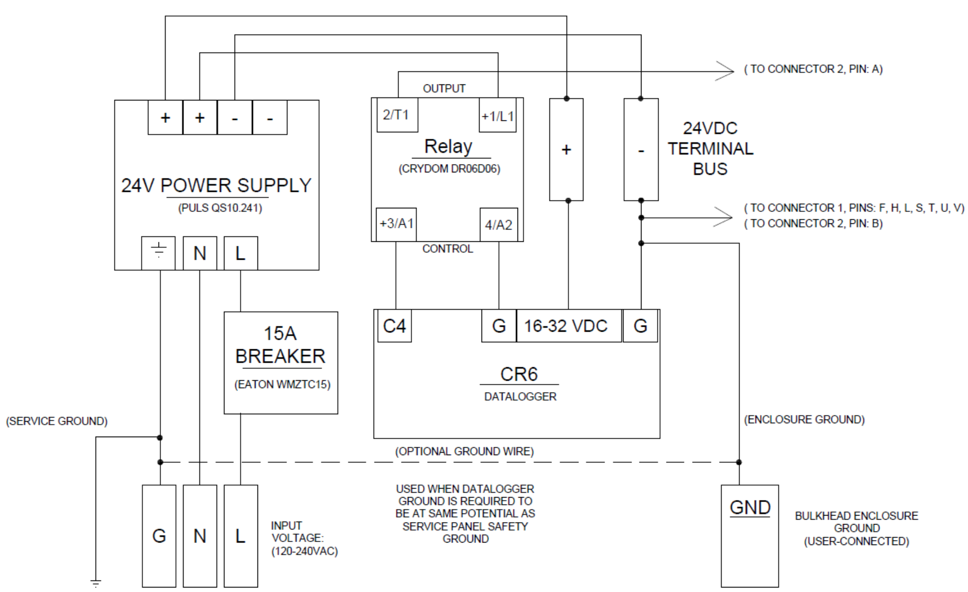

Figure 2. Block diagram of the controller

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[e]CR6 operational manual https://s.campbellsci.com/documents/us/manuals/cr6.pdf.

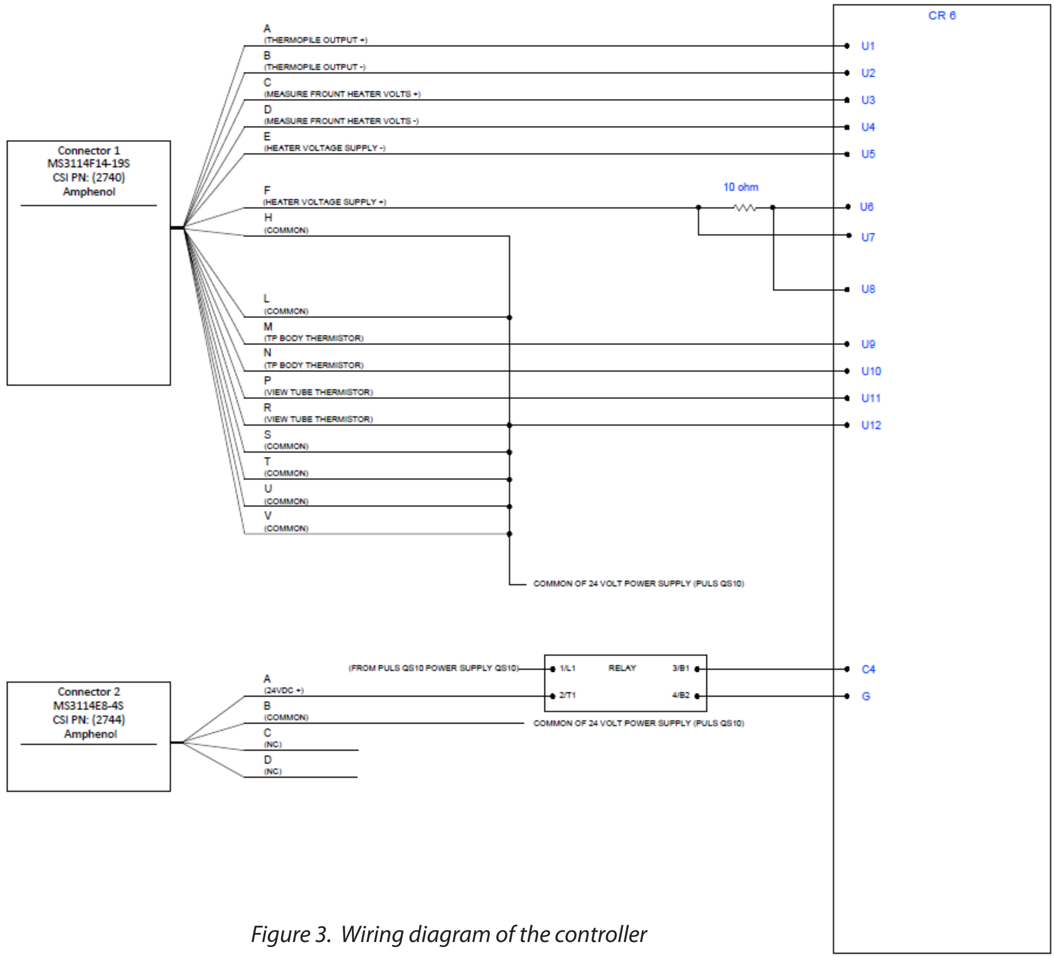

Figure 3. Wiring diagram of the controller

Procedure

The following are the sequence in the operation of the cavity outlined in a report by Ibrahim Reda of NREL, Golden Colarado.[f]

Calibration

The cavity needs to be calibrated to find a multiplication factor, M. This value is multiplied to the thermopile voltage to yield the solar irradiance in W/m^2. The following is the calibration procedure:

1. Open the cavity cover and expose it to the solar radiation for at least 40 s for thermalization.
2. Measure the thermopile voltage, *TPVS*.
3. Calculate the solar power incident by using a default sensitivity factor provided by the instrument manufacturer. Power is calculated using *Eq. 1*:

$$P = \frac{TPVS}{DS} \text{ x Area of aperture of the cavity} \qquad \textit{(Eq. 1)}$$

4. Use *Eq. 2* to calculate the voltage needed on the cavity heater to produce same amount of power. This is the method of electrical substitution mentioned earlier.

$$V = \sqrt{(PR_h)} \qquad \textit{(Eq. 2)}$$

   Where, R_h, is the heater resistance. This voltage is corrected for the lead correction resistance $R_c \sim 3\ 0{:}066\ \Omega$.

5. Cover the cavity aperture with a shutter to remove solar radiation and apply the voltage calculated above to the heater. Determine the heater current by measuring the voltage drop, V_{Rl}, across a precision current sensing resistor R_l. Also measure the voltage V_h across the heater.
6. After 60 s of thermalization, measure the thermopile voltage, TPV.
7. Set the heater voltage to zero.

[f]Ibrahim Reda, Calibration of a solar absolute cavity radiometer with traceability to the World Radiometric Reference, NREL/TP-463-20619.

8. Wait 40 s for thermalization, and then measure the thermopile voltage. This is the offset for the TPVO measurement system. This offset includes any sensor offset as well as offsets on the ADC.
9. Subtract the offset from each subsequent measurement.
10. Use *Eq. 3* to calculate the multiplication factor, M:

$$M = \frac{\frac{V_{Rl}}{R_l} \times \left(V_h - \frac{V_{Rl}}{R_l} \times R_c \right) \times C_f \times 10^4}{TPV - TPVO} \qquad (Eq.\ 3)$$

Where, V_h is the voltage measured in the heater circuit.

Measurements

After calculating the multiplication factor, open the shutter and measure the solar irradiance measurement every 30 s. Convert the thermopile voltage to solar irradiance by multiplying the thermopile voltage with the factor, *M*, obtained in *Eq. 3*, after the offset TPVO is subtracted.

The control unit was compared against four standard cavities maintained at NREL. The standard deviation of difference between our unit and NRELs standard was calculated to be 0.06.

Software

The above sequence of events was programmed into CRBasic in sequential mode. The user can input various parameters from a RTMC graphical interface. The RTMC program allowed users to input start time and stop time of the measurement in hours and minutes of the day. Users can also input, calibration time, series measurement time and interval between two meausrements. AT IPC-XII, the calibration time is 4 minutes; series measurement time is 21 minutes; and time interval between measurements is 30 s. This means a user can collect up to 42 solar irradiance measurements every 25 minutes. These values are used as default values in our program. The program makes a calibration before a 42-measurement sequence. It then saves the calibration and measurement data onto a microSD flash card using a format specified by the IPC-XII. The data file stored on the microSD card will be submitted to IPC every evening during the IPC-XII. IPC will then provide a calibration factor and some statistical uncertainty estimates at the end of the event.

The controller includes a Campbell Scientific NL240 Wi-Fi Network Link Interface allowing users to communicate with the controller using an ad hoc wireless network or by connecting to an existing Wi-Fi network. The CR6 has an Ethernet port that can also be used to connect it to an existing wired network.

Results

The controller was compared against the standard maintained at National Renewable Energy Laboratory, Golden Colorado. Figure 4 shows the measurement from AHF 28560 and NREL standard. A WRR factor of 1.00213 was provided by the NREL with a type B Standard uncertainty of 0.19%. The type A standard uncertainty was found to be 0.06%. This means that the controller presented here was within 0.06% of the standard and the standard itself has an uncertainty of 0.19%.

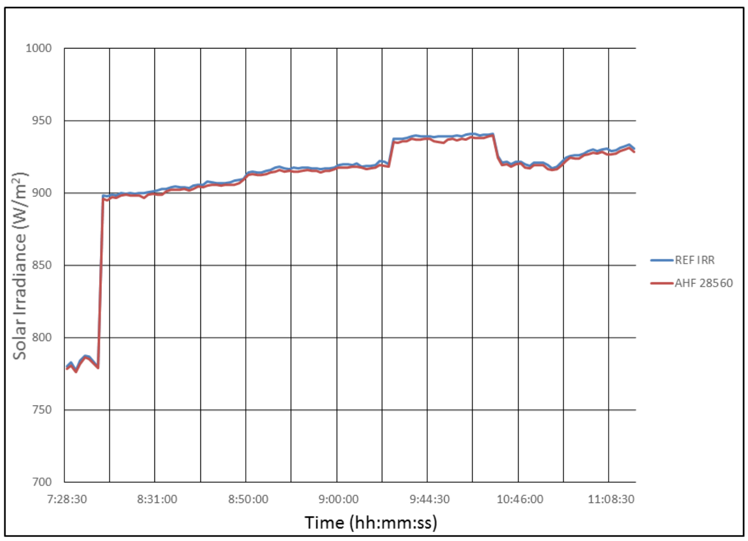

Figure 4. Comparison of Campbell Scientific's AHF Cavity controller with the standard at NREL, Golden, Colorado.

Acknowledgments

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