African Journal of Biotechnology Vol. 9(12), pp. 1719-1725, 22 March 2010
Available online at http://www.academicjournals.org/AJB
ISSN 1684–5315 © 2010 Academic Journals

Full Length Research Paper

Construction of a reliable model pyranometer for irradiance measurements

Medugu, D. W.[1]*, Burari, F. W.[2] and Abdulazeez, A. A.[2]

[1]Department of Pure and Applied Physics, Adamawa State University, Mubi, Nigeria.
[2]Department of Physics, Abubakar Tafawa Balewa University, Bauchi, Nigeria.

Accepted 30 December, 2009

There is a problem of availability of sufficient and functional instruments for measuring solar radiation in Nigeria due to the high importation costs and maintenance. In order to alleviate this problem, the design, construction and testing of a reliable model pyranometer (RMP001) was done in Mubi, Adamawa State of Nigeria. Detailed instructions were provided for assembly and calibration. Bearing cost, photodiode active-surface and signal-to-noise ratio in mind, the most suitable photodiode for this application was BPW21. The pyranometer was constructed around the photodiode held with a protective plastic case. The CMP3 pyranometer was used as a standard for calibration and comparison. A calibration constant of 5230 ± 0.02 *Wm^{-2}* was obtained. The stability of the RMP001 compared favourably with the CMP3 during a day open – sky test giving irradiances of 20.76 and 21.7 Wm^{-2} for RMP001 and CMP3, respectively, at 5:25 p.m. RMP001 will be used for the collection of authentic irradiance data for comparative evaluation with the theoretical predicted results given by researchers.

Key words: Solar radiation, pyranometer, photodiode, irradiance.

INTRODUCTION

This paper presents the design, construction and testing of a reliable model pyranometer for measuring solar irradiance (Wm^{-2}). The sensor used in the development is silicon photodiode. The constructed pyranometer possesses similar characteristics to those of standard pyranometers based on thermopiles at a significant lower price.

Measurement of solar radiation per unit of surface (Wm^{-2}) is called irradiance. Pyranometer is an instrument use for measuring solar radiation on a horizontal surface. Pyranometers are widely used in meteorology, climatelogy, agriculture, solar energy studies and building physics. The constructed pyranometer can be used in any installation where reliable measurement of solar irradiance is necessary, especially in those where cost may be a deciding factor in the choice of a meter.

A number of formulae and methods have been developed to estimate irradiance at different places in the world. But because of the differences in local climatic conditions, the suggested radiation models for one location may not successfully apply to other places. The availability of meteorological parameters which are used as the input to radiation models is an important key in choosing the proper radiation models at any location. Among all such meteorological parameters, sunshine hour, latitude and cloud cover are the most widely or commonly used parameters to predict daily global radiation and its components at any location.

The tropical Nigeria has made solar energy availability unequal and the average is 3.7 $KWhm^{-2}day^{-1}$ along the coastal areas to about 7.0 $KWhm^{-2}day^{-1}$ along the semi arid areas of the North. The country however, on the average receives solar radiation level of about 5.3$KWhm^{-2}day^{-1}$ (ECN, 2005). Most researchers within the country use these available theoretical values of mete-orological data to compute average irradiance of solar radiation for different locations within Nigeria. They lack standard measured data obtained from reliable mea-suring instrument suitable for their local environment and therefore resorted to theoretical predictions using diffe-rent models for the global daily sunshine radiation. Examples of such models in the Nigerian environment include that of Burari and Sambo (2001), Madekwe and Ogunmola (1997), Sambo and Doyle (1985) and Fagbenle (1983) to mention but a few. The need for developing a standard pyranometer for the collection of authentic irradiance data for comparative evaluation with the theoretical predicted

*Corresponding author. E- mail: dalemedugu@yahoo.com.

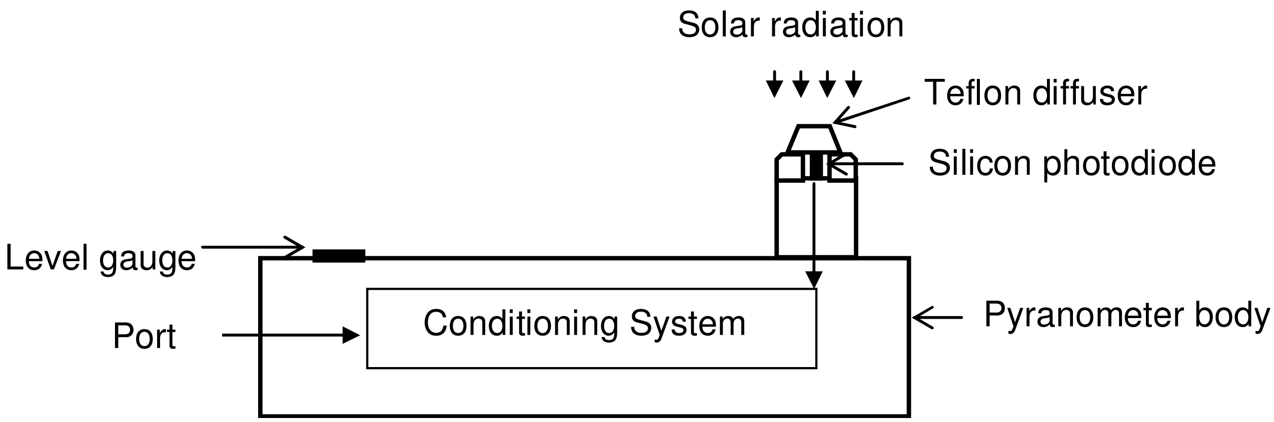

Figure 1. Pyranometer block diagram.

results given by previous resear-chers becomes a necessity. This major reason among many others prompted the emergence of this study.

SYSTEM DESCRIPTION AND DESIGN IMPLEMENTATION

The developed pyranometer is shown outlined in its housing in Figure 1. The sensor element is a silicon diode, mounted on a plastic base, covered with a teflon diffuser. The whole unit is placed on a base with a level control to ensure horizontality.

The developed pyranometer generates an electrical signal proportional to the irradiance received and converts the small current received from the detector to a voltage and amplifies it to a voltmeter.

Each of the systems and elements with which the pyranometer is equipped will be described below. They are shown as a block diagram in Figure 1 and as a circuit diagram in Figure 2.

Radiation diffuser and pyranometer housing

As a protective element for the detector and at the same time a solar radiation diffuser (see Figure 1), a teflon diffusing disk was mounted over the photodetector assembly with a great deal of care to improve its cosine response. To a large extent, this diffuser allows elimination of the cosine error (Michalsky et al., 1995; King et al., 1997; Beaubien et al., 1998). Teflon was used because it is a good diffuser and is also resistant to the elements and ultra-violet (UV) radiation (Lowry et al., 1991; Bernhard and Seckmeyer, 1999), given its capability to diffuse transmitting lights nearly perfectly. Moreover, the optical properties of Teflon remain constant over a wide range of wavelengths, from UV up to near infrared. Within this region, the relation of its regular transmittance to diffuse transmittance is negligibly small, so light transmitted through a diffuser radiates like Lambert's cosine law.

Most commercial pyranometers use a glass dome which, apart from being more expensive than the Teflon diffuser used in this pyranometer, becomes affected by continuous solar radiation and traps higher amounts of dirt (Feuermann and Zemel, 1993). As a result, it must be replaced frequently to ensure device precision. The Teflon diffuser is housed together with the photodiode in the top of the pyranometer and is joined onto the rest of the body via five minutes epoxy, which allows complete air-tightness in the unit (see Figure 3).

The pyranometer housing contains the photodiode and all the signal conditioning and distribution electronics. It is manufactured from a single piece of 10 mm thick plastic, since plastic is a material which resists the elements very well and also shows excellent characteristics as a thermal insulator. Figure 3 shows the body of the developed pyranometer. It highlights the location of the watertight connection for data input/output and the level gauge (to achieve complete horizontality of the device).

Detector

The most common types of detectors used to measure radiation are thermoelectric and photoelectric.

Thermoelectric detectors measure temperature differrences using a thermocouple or thermistor as a transducer to convert radiant energy to electrical energy. They are used mainly for solar and long wave radiation measurements and have the property of equal response over their wavelength range.

The photoelectric types, here referred to as photodiodes, are solid-state devices that convert light energy (photons) to electrical current (Pearcy, 1989; Hamamatsu Corp., 1995). Photoelectric detectors are particularly useful for measuring the light required by plants for photosynthesis, because they respond to the photon flux over the photosynthetically active wavelengths.

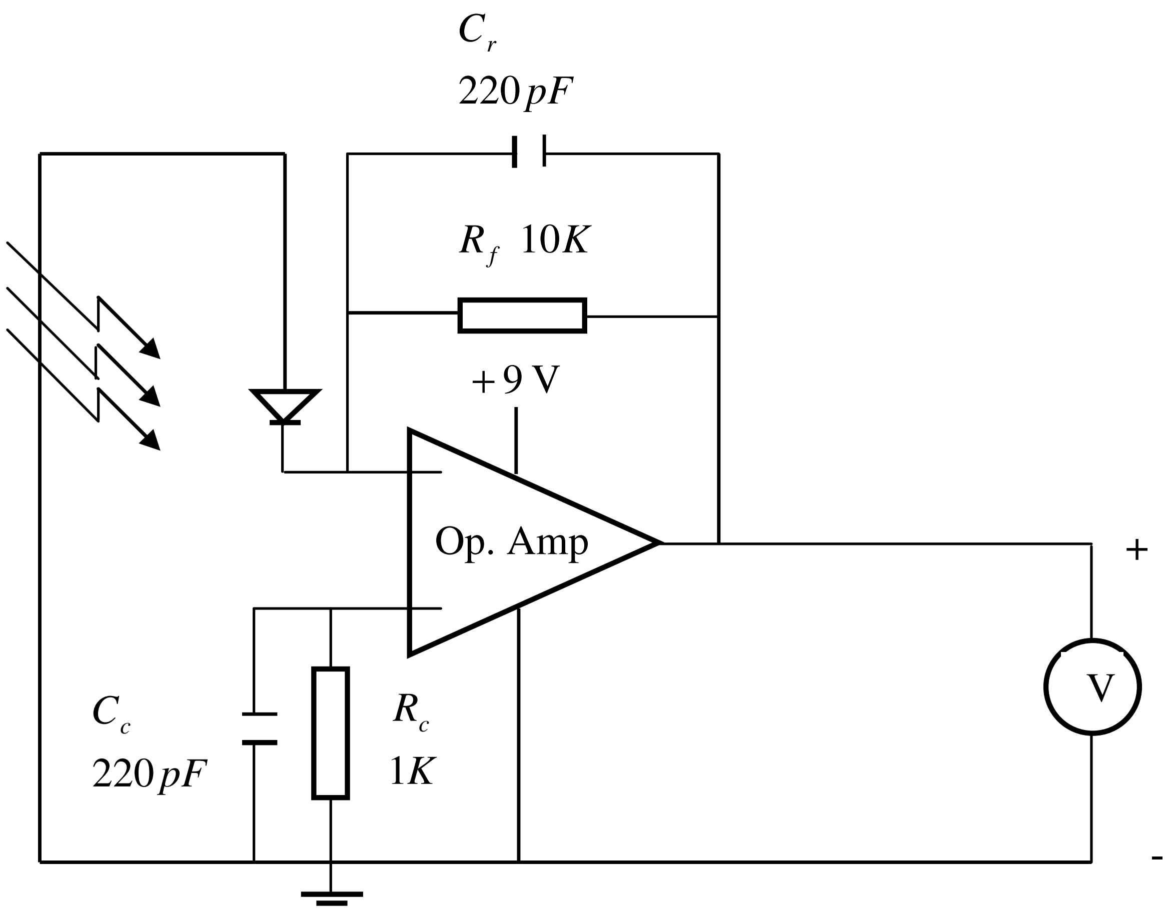

Figure 2. Pyranometer circuit diagram.

The choice of pyranometer detector (photodiode) has required an exhaustive study of the commercial devices available, since it constitutes one of the key elements to being able to obtain better performance from the developed pyranometer. A photodiode was required with a response within the visible spectrum (Kaufmann, 2009), a high value and as linear as possible.

In the search for the best detector we worked in using the characteristics in the datasheets supplied by the manufacturers. Bearing cost, photodiode active-surface and signal-to-noise ratio in mind, it was decided that the most suitable photodiode for this application was BPW21.

Conditioning System

The transimpedance amplifier shown in Figure 4, configured around the LTC1051 operational amplifier (OPAM), was used for signal conditioning from the photodiode (see Figure 2). In this circuit, *Ip* is the photocurrent from the diode and *C* its parasitic capacitor. *Cc*, *Rc* and *Cr* are compensation, correction and stabilization elements, respectively. Their value and function shall be seen later. Finally, *Rf* is the feedback resistor which fixes the DC gain in the circuit, so the output from this is *V0* = *Ip Rf*. Note that the noise current in the photodiode has not been taken into consideration, since the BPW21 has an excellent SNR.

To calculate the value of R_f a nominal irradiance of 1,000 W/m^2 was used. For this, the BPW21 photodiode produces the photocurrent *Ip* = 4.68 × 10^{-4}A. Therefore, the value of *Rf* implemented was 470Ω, to carry out precise adjustment. In order to correct the DC error due to polarization currents, a resistor (*Rc*) was connected to the non-inverting input of the OPAM. This resistor has a detrimental effect in terms of noise (Graeme, 1996), which is amplified; this is why a 100*pF* compensation capacitor *Cc* is connected in parallel with it. The parasitic capacitor on the photodiode BPW21, *C*, is 580*pF*. This capacitor has to be taken into consideration, as it can influence the stability of the assembly (reducing its phase margin and therefore, its relative stability). To improve the stability of the amplifier, finally, a capacitor *Cr* is connected in parallel with the feedback resistor *Rf* (see Figure 2). It is calculated that an appropriate value for the capacitor is 100 pF.

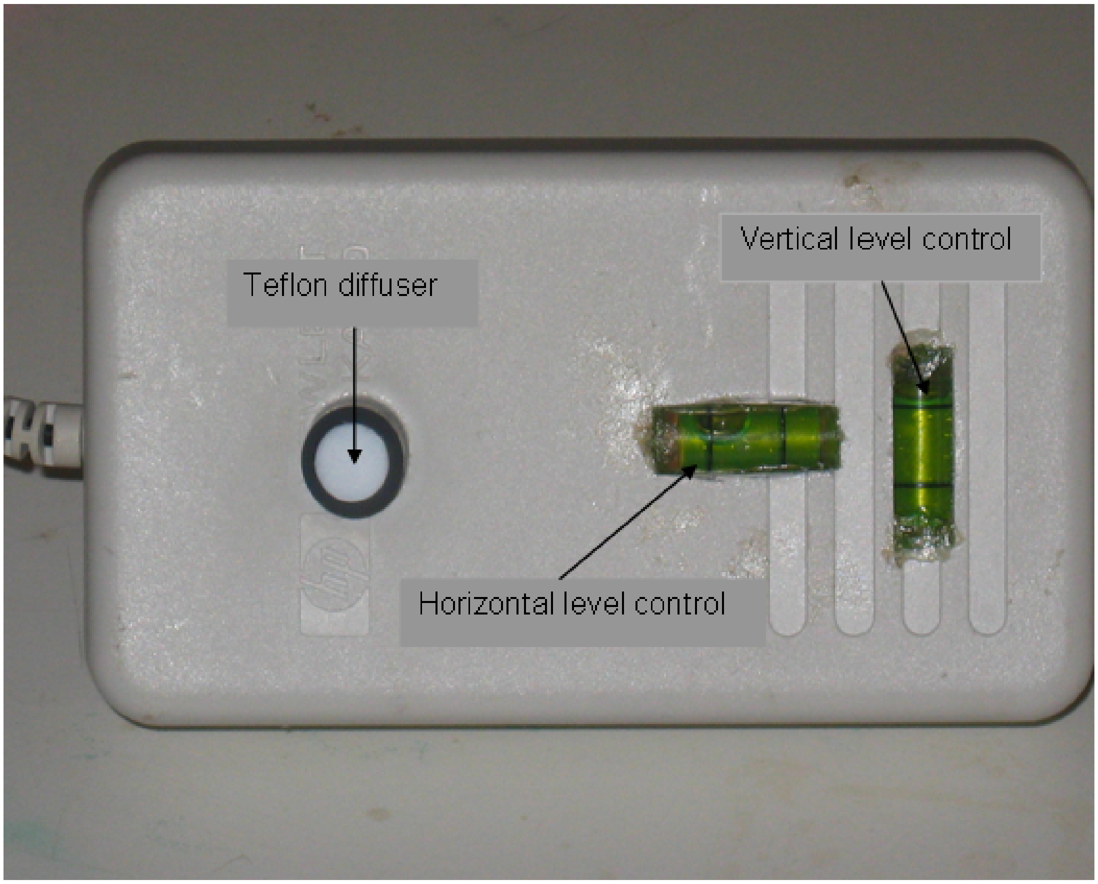

Figure 3. Body of the developed pyranometer.

METHOD OF CONSTRUCTION

A hole was drilled about one quarter distance from one end in the top of the plastic case. A plastic LED holder was inserted into the hole and super glued. The photodetector was inserted into the LED holder. Another two holes were also drilled opposite to where photodetector was placed. These holes were for the purpose of inserting level gauges to ensure horizontality and verticality of the instrument. A small hole was also drilled in the center of the opposite end of the enclosure from the hole (on the side of the enclosure, not the top). This hole was large enough for a grommet, through which a connecting cable is passed. Several centimeters of the cut end of the plug and cable assembly were assembled through the grommet, from the outside to the inside of the case. The transimpedance amplifier configured around the LTC1051 operational amplifier (OPAM) was then fixed into the case. The photodiode and the connecting cable were soldered to the input and output of the OPAM, respectively.

The Teflon diffusing disk was finally mounted over the photodetector assembly with a great deal of care. When convinced that the pyranometer was working properly, the bottom of the case was attached with the screws.

RESULTS AND DISCUSSION

Calibration

After the pyranometer had been constructed and tested according to the specifications and methodology described, the next step was the calibration of it.

Calibration is the process of deriving a coefficient to convert the raw signal from the model pyranometer to readily quantifiable units. In this case, after the pyranometer had been constructed and tested, the output was calculated into irradiance units of Wm^{-2}. Calibration of instruments that measures radiation is an ongoing challenge and there are many scientists who have devoted their professional careers to understanding and maintaining absolute radiometric standards.

A pyranometer can be calibrated under clear sky conditions by using a so-called radiative transfer model of solar transmission through the atmosphere. This is a somewhat circular approach to calibrating instruments that are intended to be very accurate, because it assumes knowledge of just those characteristics of the atmosphere (water vapor and aerosols, for example) that affected the amount of energy being transmitted to earth's surface. However, this approach will yield a reasonable approximate calibration.

For this reliable model pyranometer (RMP001) constructed, a reasonable approach was to calibrate it against a reference high quality pyranometer, Kipp and Zonen CMP 3 whose calibration was trusted (14.71 ±

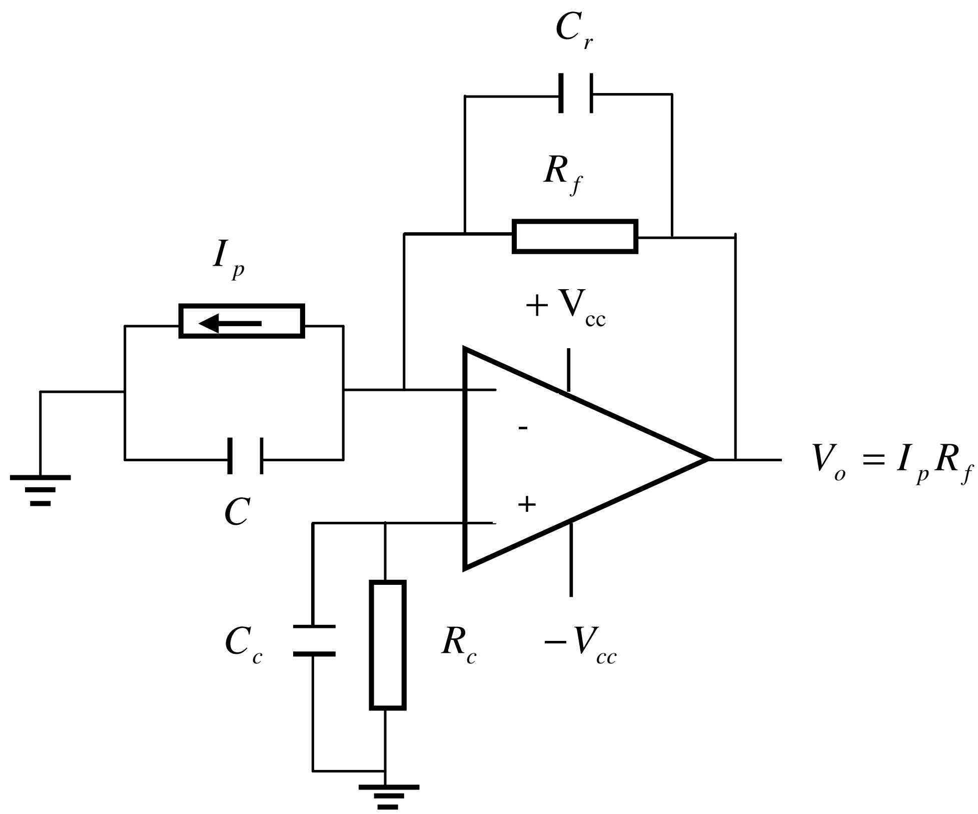

Figure 4. Transimpedance amplifier to condition the *Ip* signal provided by the photodiode.

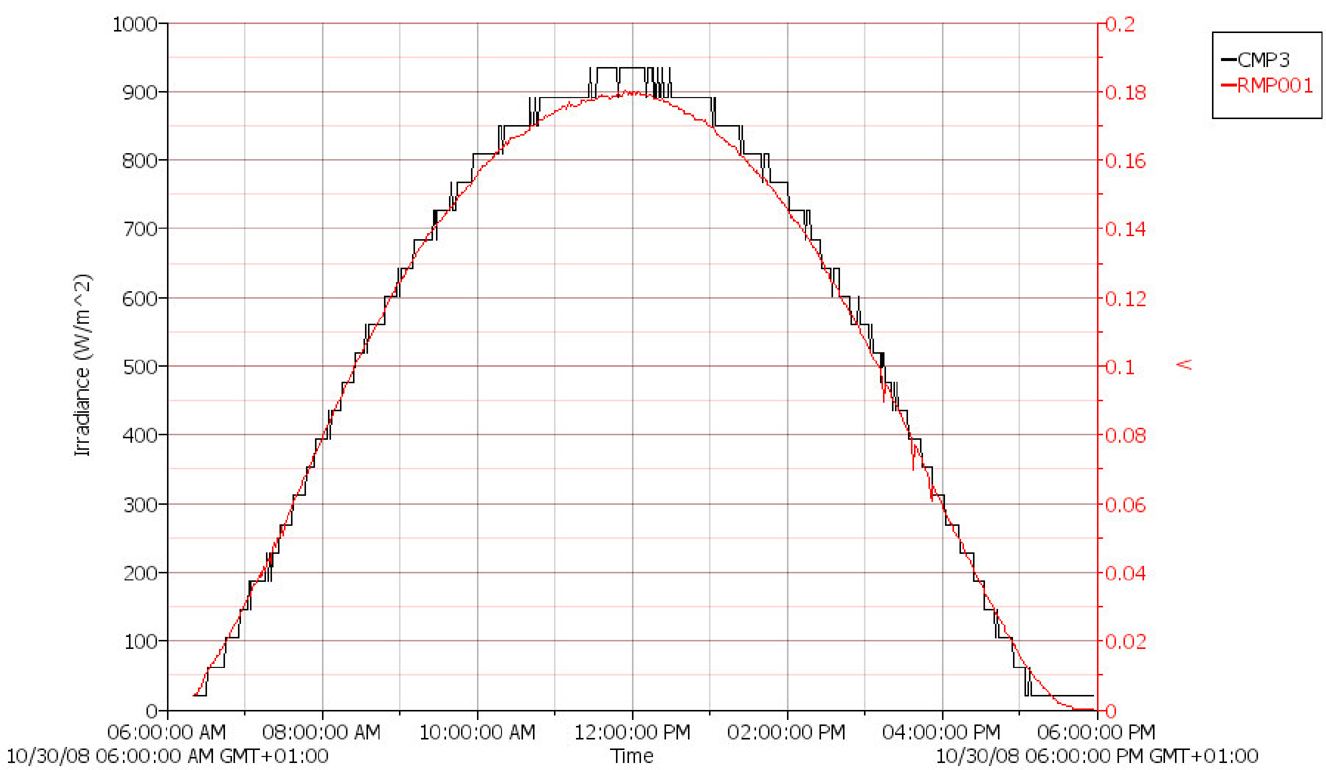

Figure 5. Graph of Solar Radiation measured with CMP3 and RMP001verses Time on 30th October, 2008.

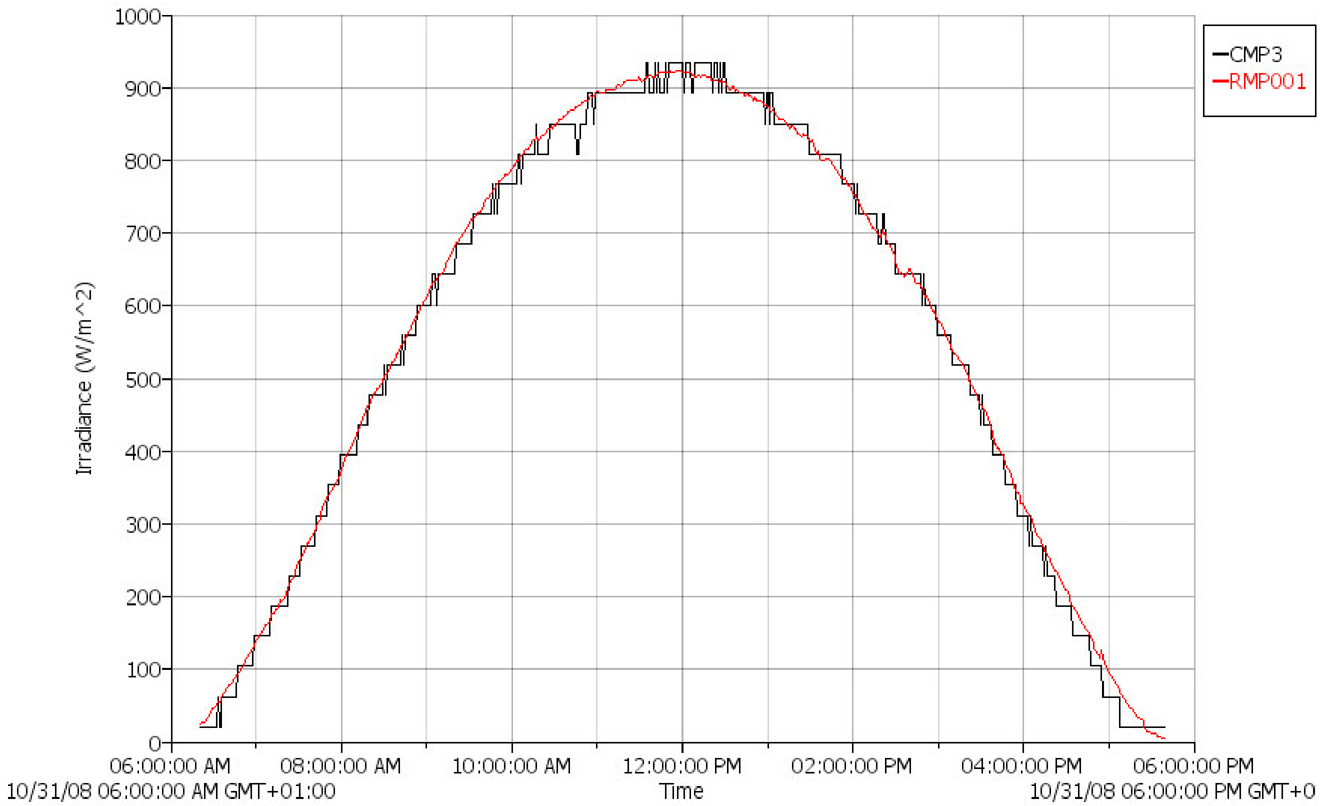

Figure 6. Insolation graph covering 31st October, 2008 at Adamawa State University, Mubi using both CMP3 and RMP001 after calibration adjustments and model maximum values of insolation have been entered.

0.36 μV/W/m^2). The pyranometer was mounted beside the reference pyranometer and data was collected under open skies for a full day, 6.00 a.m. to 6.00 p.m. and stored at an interval of 1 min. The readings of irradiance obtained were in Wm^{-2} and V for the CMP3 pyranometer and RMP001, respectively, as shown in Figure 5. The process of calibrating the pyranometers constructed to the elements was carried out following the ISO 9847 standard (Solar Energy, 1992), by comparison with a standard pyranometer (SP), specifically the Kipp and Zonen CMP 3 which belongs to the secondary standard class, or the best. Pyranometers are standardized according to the ISO 9060 standard in 1990, which is also adopted by the World Meteorological Organization (WMO). This standard discriminates three classes. The best is (confusingly) called secondary standard, the second best first class and the last one second class.

The output from this instrument is about 0.02783, 0.1547, 0.17853, 0.1468 and 0.0592 V at 7.00a.m., 10.00a.m., near noon, at 2.00p.m. and 4.00p.m. in full sunlight, for irradiance of 145.48, 808.97, 933.37, 767.50 and 311.35 Wm^{-2} respectively. The conversion of the output from RMP001 from volts to Wm^{-2} was done to obtain the calibration constant as follows:

At 7.00a.m.

$$0.0278V = 145.48Wm^{-2}$$

$$1V = \frac{145.48}{0.0278} = 5233.09Wm^{-2}$$

At 10.00a.m.

$$1V = \frac{808.97}{0.1547} = 5229.28Wm^{-2}$$

Near noon

$$1V = \frac{933.37}{0.17853} = 5228.08Wm^{-2}$$

At 2.00p.m.

$$1V = \frac{767.50}{0.1468} = 5228.20Wm^{-2}$$

At 4.00p.m.

$$1V = \frac{311.35}{0.0592} = 5229.29Wm^{-2}$$

$$Mean = 5229.59 \approx 5230 \pm 0.024 Wm^{-2}$$

This calibration constant obtained for RMP001 produces the best fit with the calibrated output.

Testing

In order to test the pyranometer, its output needed to be recorded. Insolation data at 1 min intervals was recorded for Mubi, Adamawa State-Nigeria, using a data logger. The logger has a USB interface with proprietary software for communicating with a computer. The data was stored in a propriety binary format and later saved as a text file that was imported into excel. The plot of insolation against time for both pyranometers is displayed in Figure 6. From Figure 6, it is seen that at the initial time, that is 6:21a.m., the irradiance taken with the constructed pyranometer (RMP001) and the standard reference pyranometer (CMP3) were 23.94 and 21.07 Wm^{-2}, respectively. The highest irradiance occurred at 11:52a.m. with irradian-ces of 923.80 and 933.37 Wm^{-2} for RMP001 and CMP3, respectively. At 5:25 p.m., the irradiances were 20.76 and 21.7 Wm^{-2} for RMP001 and CMP3, respectively.

Conclusion

This paper presents the design, construction and testing of a reliable model pyranometer for measuring solar irradiance. Construction of the pyranometer is conceptually very simple and cheap. However, it was designed based on an understanding of the underlying physical principles. The pyranometer was then calibrated against a reference high quality Kipp and Zonen CMP3 pyranometer whose calibration was trusted to obtaina calibration constant of $5230 \pm 0.024 Wm^{-2}$. It was finally studied under actual environmental conditions of Mubi, Adamawa State of Nigeria. Tests carried out on the constructed pyranometer show it can compute favorably with the standard reference pyranometer (CMP3).

The newly developed pyranometer can be used in any installation where reliable measurement of solar irradiance is necessary, especially if cost becomes a deciding factor when choosing a pyranometer.

REFERENCES

Bernhard G, Seckmeyer G (1999). The uncertainty of measurement of spectra, Solar UV irradiance. J. Geophys. Res., 104: 14321-14345.

Beaubien DJ, Bisberg A, Beaubien AF (1998). Investigations in pyranometer design. J. Atmosph. Ocean. Tech. 15: 677-686. Burari FW, Sambo AJ (2001). Models for the Predictions of Global Solar Radiation for Bauchi using Meteorological Data. Nig. J. Renewable Energy, 9: 30-33.

Energy Commission of Nigeria (ECN) (2005). Renewable Energy Master Plan. pp. 44-67.

Feuermann D, Zemel A (1993). Dust-induced degradation of pyranometer sensitivity. Solar Energy, 50: 483-486.

Fagbenle RO (1983). Estimation of Total Solar radiation In Nigeria using Meteorological Data. Paper presented at the 3rd National Solar Energy Forum (NASEF), Bidda.

Graeme J (1996). Photodiode amplifiers. Op amp. solutions. Mc-Graw Hill: NY, USA, pp. 24-59.

Kaufmann K (2009). Choosing your detector. Hamamatsu Corp. Available Onlineat:http://sales.hamamatsu.com/assets/applications/Combined/choosing-detector.pdf.

King DL, Kratochvil JA, Boyson WE (1997). Measuring Solar Spectral and Angle of Incidence Effects on Photovoltaic Modules and Solar Irradiance Sensors. In Proceedings of the 26th PVSC, Anaheim, CA, USA, pp.1113-1116.

Lowry JH, Mendlowitz JS, Subramanian NS (1991). Optical characteristics of the Teflon AF fluoroplastic materials. Proc. SPIE. San Diego, CA, USA, 1330: 142-151.

Madekwe AAL, Ogunmola A (1997). Estimation of the Monthly Average Atmospheric Perceptible Water Vapor and its Relationship with Global Solar Radiation. Nig. J. Phys. 9: 20-26.

Michalsky JJ, Harrison LC, Berkheiser WE (1995). Cosine response characteristics of some radiometric and photometric sensors. Solar Energy, 54: 397-402.

Pearcy RW (1989). Radiation and Light Measurements in Plant Physiological Ecology: Field Methods and Instrumentation. Chapmand and Hall, London, U.K. pp. 97-116.

Sambo AS, Doyle MDC (1985). Estimation of the Global and Diffuse Components of Solar Radiation for some Nigerian cities, Nig. J. Solar energy, 5: 16-22.

Solar Energy (1992). Calibration of field pyranometers by comparison to a reference pyranometer, ISO 984.