MEASUREMENT AND PREDICTION OF GLOBAL SOLAR RADIATION OVER MAIDUGURI, NIGERIA

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Abstract
Measurement and prediction of global solar radiation over Maiduguri were carried out. The measurement was done with the aid of a constructed Reliable Model Pyranometer (RMP002) while the prediction was carried out using Angstrőm–Prescott theoretical model based on sunshine duration. A good agreement between measured and predicted values of this global solar radiation for all months is clear. According to the statistical test results, the values of RMSE and MBE were in the acceptable ranges of $5.41Wm^{-2}$ and 18.74 Wm^{-2}, respectively. The calculated t-statistics value is about 1.0001, which is less than the critical t value (1.96). RMP002 can conveniently be used in any installation where reliable measurement of solar radiation is necessary, especially in those where cost may be a deciding factor in the choice of a meter.

Key words: Measurement; prediction; pyranometer; angstrőm–prescott; t-statistics.

Introduction

In many applications of solar energy, the most important parameters that are often needed are the average global solar irradiation and its components. Unfortunately, the measurements of this parameter are done only at a few places. Since there is a very low spatial density of meteorological stations equipped for radiation observations in developing countries, the numerical methods become a useful alternative. Most of the correlation models for estimating solar radiation values are based on sunshine duration.

The best way of knowing the amount of global solar radiation at a site is to install Pyranometers at many locations in the given region and look after their day-to- day maintenance and recording, which is a very costly exercise. In such situations, the use of solar radiation models to estimate the data needed for solar energy applications is a common practice (Supit and Van Kappel, 1998; Meza and Varas, 2000; Revfeim, 1997; Ododo, 1997; Canada, 1988). One approach is to correlate the global solar radiation with the meteorological parameters at the place where the data is collected. The resultant correlation may then be used for locations of similar meteorological and geographical characteristics at which solar data are not available. Another approach is to construct an alternative inexpensive pyranometer.

This paper presents the measurement and prediction of global solar radiation over Maiduguri. The measurement was done with the aid of a constructed Reliable Model Pyranometer (RMP002) while the prediction was carried out using Angstrőm–Prescott theoretical model based on sunshine duration. The need for radiation data covering entire areas led to the development of the Pyranometer. The constructed Reliable Model Pyranometer presents some characteristics and features to those of standard pyranometer at a price which is tens of times lower. The results obtained from the constructed Reliable Model Pyranometer will be compared to the predicted results in order to be conscious 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.

Maiduguri is the capital of Borno State in Nigeria. It is located on the north bank of the seasonal Ngadda (Alo) River, the waters of which disappear in the *firki* (“black cotton”) swamps just southwest of Lake Chad, about 113 km northeast. The city lies on latitude $11^{0}50'$ and longitude $13^{0}09'$ and within the semi-arid zone of northeastern Nigeria. The British founded the city in 1907 as a military outpost. The city eventually grew into one of the largest cities in Northern Nigeria. The city falls within the Sahel zone of the Nigeria's vegetation zones.

Angstrőm–Prescott Model

The most generally used prediction method was developed by Angstrőm, and later modified by Prescott. The modified version of Angstrőm–Prescott has been the most convenient and widely used correlation for estimating the global radiation. The formula is (Duffie and Beckman,1994):

$$\frac{H}{H_0} = a + b\frac{S}{S_o} \qquad (1)$$

where, H and H_0 are, respectively, the global radiation (MJm^{-2}day^{-1}) and the extraterrestrial solar radiation on a horizontal surface (MJm^{-2}day^{-1}); S and S_0 are, respectively, number of hours measured by the sunshine recorder and the maximum daily sunshine duration(or day length); and a,b are regression constants to be determined.

Regression equation (1) has been found to accurately predict global solar radiation in several locations (Akpabio, 1992).

For monthly average, this formula holds (Duffie and Beckman,1994):

$$\frac{\bar{H}}{\bar{H}_0} = a + b\frac{\bar{S}}{\bar{S}_o} \qquad (2)$$

Here, $\bar{H}$ is the monthly average daily global radiation on a horizontal surface (MJm^{-2}day^{-1}), $\bar{H}_o$ is the monthly average daily extraterrestrial radiation on a horizontal surface (MJm^{-2}day^{-1}), $\bar{S}$ is the monthly average daily number of hours of bright sunshine, $\bar{S}_o$ is the monthly average daily maximum number of hours of possible sunshine.

Regression coefficient a and b have been obtained from the relationship given as (Tiwari and Sangeeta, 1977) and also confirmed by (Frere et al. 1980)

$$\begin{aligned} a &= -0.110 + 0.235\cos\phi + 0.323(S/S_o) \\ b &= 1.449 - 0.553\cos\phi - 0.694(S/S_o) \end{aligned} \qquad (3)$$

Whereas there are many methods to evaluate these constants.

The extraterrestrial solar radiation on a horizontal surface can be calculated from the following equation (Duffie and Beckman,1994):

$$H_o = \frac{24x3600}{\pi} I_{sc}\left[1 + 0.033\cos\left(360\frac{dn}{365}\right)\right] \left[\left(\frac{2\pi\omega_s}{360}\right)\sin\phi\sin\delta + \cos\phi\cos\delta\sin\omega_s\right] \qquad (4)$$

The value of $1367Wm^{-2}$ has been recommended for solar constant I_{sc} (Frolich and Brusca, 1981).

The hour angle ω_s for horizontal surface is given as (Duffie and Beckman,1994):

$$\omega_s = \cos^{-1}(-\tan\phi\tan\delta) \qquad (5)$$

Declination is calculated as (Cooper, 1969):

$$\delta = 23.45\sin\left(360\frac{284 + dn}{365}\right) \qquad (6)$$

Where dn is the day of the year from January 1 to December 31.

The day length S_o is the number of hours of sunshine or darkness within the 24 hours in a given day. For a horizontal surface it is given by (Duffie and Beckman,1994):

$$S_o = \frac{2}{15}\cos^{-1}(-\tan\phi\tan\delta) = \frac{2}{15}\omega_s \qquad (7)$$

(from equation (5)).

The Reliable Model Pyranometer (RMP002)

The pyranometer is shown in Figure 1 outline in its housing and as a circuit diagram in Figure 2. 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 best detector was chosen based on the characteristics in the datasheets supplied by the manufacturers. The most suitable photodiode for this application was BPW21with responsivity, sensitive area and noise equivalent power of 0.34A/W, $7.34 \times 10^{-6} m^2$ and $7.2 \times 10^{-14} W/Hz^{1/2}$ respectively.

Construction of solar cell – based pyranometers are conceptually very simple and cheap. However, they require care design based on an understanding of the underlying physical principles.

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

The transimpedance amplifier shown in Figure 3, is configured around the LTC1051 operational amplifier (OPAM) in order to condition signal from the photodiode as shown in Figure 2. In this circuit I_p is the photocurrent from the diode and C its parasitic capacitor. C_c, R_c Cr are compensation capacitor, correction resistor and stabilization capacitor respectively. The feedback resistor R_f fixes the DC gain in the circuit in order to obtain an output from $V_0 = I_p R_f$.

An irradiance of 1,200 W/m^2 obtained from a 200-W quartz tungsten halogen lamp is used to calculate the value of R_f. For this, the BPW21 photodiode produces the photocurrent $I_p = 3.0 \times 10^{-3}$A (i.e. $Ip.=$ irradiance x sensitive area x responsivity). In order to carry out precise adjustment for maximum Analogue-to-Digital Converter of 3v, the value of R_f implemented is 1KΩ (from $R_f = V_o/I_p$).R_c with value of 1KΩ is connected to the non-inverting input of the OPAM for correcting the DC error due to polarization currents. Any resistor connected in such a manner should have a detrimental effect in terms of noise which is amplified (Graeme, 1996); hence a 68pF compensation capacitor C_c is connected in parallel with it. The parasitic capacitor on the photodiode BPW21, C, is 580pF which influence the stability of the assembly. Finally, a 68pF capacitor C_r is connected in parallel with the feedback resistor R_f to perfect the stability of the amplifier, (see Figure 2).

The reliable model pyranometer was then calibrate against a reference high quality pyranometer, Kipp & Zonen CMP 3 whose calibration was trusted ($14.71 \pm 0.36 \mu V^{-1} Wm^{-2}$) obtaining a calibration constant of $4550 \pm 0.03 Wm^{-2}$.

Figure 1: Picture of the Constructed Reliable Model Pyranometer

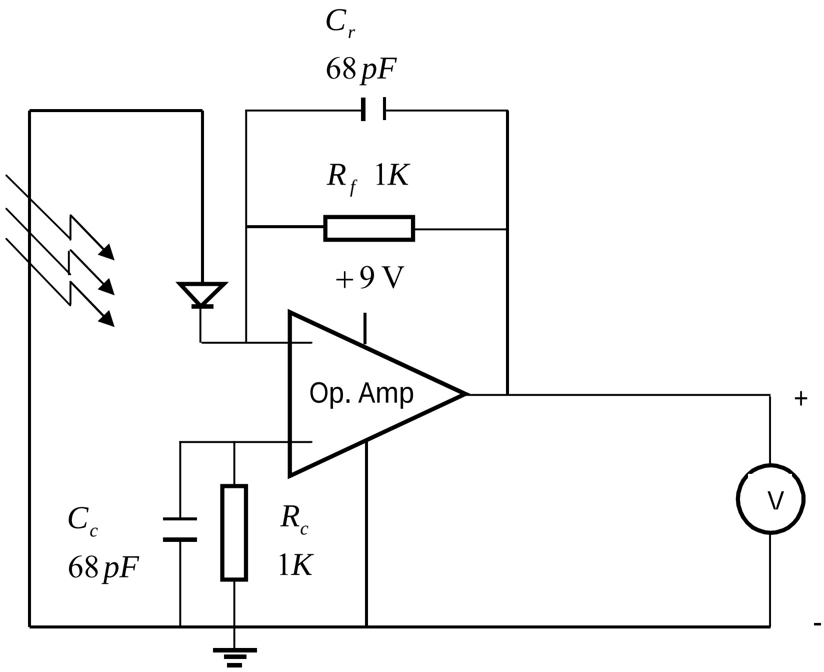

Figure 2: Pyranometer circuit diagram.

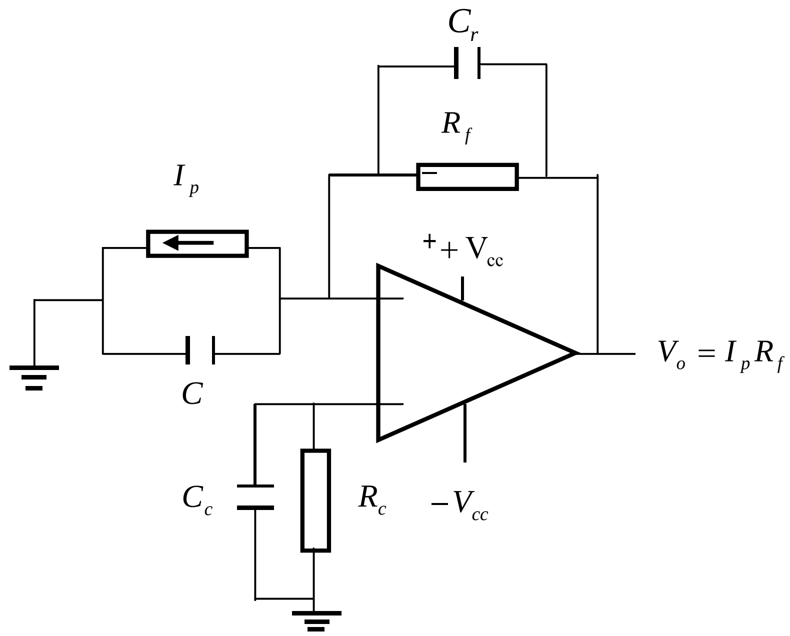

Figure 3: Transimpedance amplifier circuitry

Methodology

Measurement of solar radiation for a location in Maiduguri, Borno State of Nigeria, was obtain with the aid of RMP002 for a period of twelve months from November 3, 2008 through November 6, 2009. The instrument was set in the meteorological station under geography department of university of Maiduguri. The picture of the instrument is shown in Figure 1. Data at 1 min intervals was recorded using a HOBO 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. Daily average value of solar radiation was then determined in Wm^{-2}. The daily sunshine hour data were collected for the same period from the university's meteorological station. The relevant meteorological and solar radiation data like H, H_o, S/S_o, ω, δ, a and b calculated from equations (1) – (7) are presented. The global solar radiation data measured in ($MJm^{-2}day^{-1}$) was converted to (Wm^{-2}) using a factor of $11.6Wm^{-2}$ (http://www.fao.org/docrep). This present work is presented in Tables 1.

Statistical Model Validation

In this study, the following statistical tests were used to evaluate the accuracy of the constructed reliable model pyranometer: the mean bias error (MBE), root mean bias error (RMSE) and t-statistic. These error terms are deduced using the following equations:

$$MBE = \frac{1}{n}\sum_{i=1}^{n} d_i \quad (8)$$

$$RMSE = \left(\frac{1}{n}\sum_{i=1}^{n} d_i^2\right)^{1/2} \quad (9)$$

$$t = \left[\frac{(n-1)MBE^2}{RMSE^2 - MBE^2}\right]^{1/2} \quad (10)$$

where n is the number of data pairs and d_i is the difference between the measured and predicted values.

A low MBE is desired. A positive value gives the average amount of over-insolation in the measured value and vice-versa. A drawback of this test is that over-insolation of an individual observation will cancel under-insolation in a separate observation. RMSE test provides information on the short-term performance of the correlations by allowing a term-by-term comparison of the actual deviation between the measured value and the predicted value; the smaller the value, the better the pyranomter's performance. However, a few large errors in the sum can produce a significant increase in RMSE. The smaller the value of t, the better is the model's performance. To determine whether a model's predicts are statistically significant, one simply has to determine a critical t value obtainable from standard statistical tables, that is., $t_{\alpha/2}$ at the α level of significance and (n-1) degrees- of- freedom. For the model's predicts to be judged statistically significant at the $1-\alpha$ confidence level, the calculated t value must be less than the critical t value.

Results and Discussion

Table 1 shows the monthly mean daily global solar radiation measured with RMP002 and predicted with the aid of Angstrőm–Prescott theoretical model based on sunshine hour duration while the Mean Bias Error (MBE), Root Mean Square Error (RMSE) and t-Statistics are presented in Table 2.

The variation of the daily global radiation measured and predicted for Maiduguri is represented in Figure 4. Considering the overall result, a good agreement between measured and predicted global solar radiation for all months is clear, the maximum global solar radiation occurred in the month of March 2009 with amount of 284.70 Wm^{-2} and 255.78 Wm^{-2} for measured and predicted values, respectively as shown. 226.70 Wm^{-2} and 223.65 Wm^{-2} were respectively the minimum global radiation in the months August 2009 and October 2009. The maximum values occurred during the winter period while the minimum occurred during the summer period.

The performance of the pyranometer developed was tested statistically by validating the stimulated radiation values as compared with the measured values as shown in Table 2. According to the statistical test results, the values of RMSE and MBE were in the acceptable ranges of 5.41Wm^{-2} and 18.74 Wm^{-2}, respectively. The comparison between the measurement and prediction was carried out according to the t-statistic value, because this statistic is more effective for determining the statistical properties. For all the whole period, the calculated t value is about 1.0001, which is less than the critical t value (1.96).

Table 1: Correlation between Predicted and Measured values of monthly average daily global radiation

Month	$\bar{S}/\bar{S}_o$	a	b	$\bar{H}_o$ $MJm^{-2}d^{-1}$	$\bar{H}$ predicted $MJm^{-2}d^{-1}$	$\bar{H}$ predicted Wm^{-2}	$\bar{H}$ measuerd Wm^{-2}
Nov, 2008	0.78	0.37	0.36	31.61	20.57	237.80	251.72
Dec, 2008	0.77	0.37	0.37	30.15	19.75	229.10	229.55
Jan, 2009	0.77	0.37	0.37	31.12	20.38	236.41	229.59
Feb, 2009	0.70	0.35	0.41	33.78	21.52	249.63	262.79
Mar, 2009	0.60	0.31	0.49	36.51	22.05	255.78	284.70
Apr, 2009	0.52	0.29	0.54	37.95	21.66	251.26	263.62
May, 2009	0.50	0.28	0.56	37.89	21.24	246.38	245.38
Jun, 2009	0.51	0.29	0.55	37.51	21.40	248.24	251.53
Jul, 2009	0.52	0.29	0.54	37.56	21.44	248.70	242.88
Aug, 2009	0.48	0.28	0.57	37.69	20.86	241.98	226.70
Sept,2009	0.49	0.28	0.57	36.81	20.59	238.84	250.92
Oct, 2009	0.50	0.28	0.56	34.44	19.28	223.65	233.32
$\sum$	7.14	3.76	5.89	423.02	250.74	2907.77	2972.7
Mean	0.60	0.31	0.49	35.25	20.90	242.31	247.73

Table 2: Statistical Test Results

$MBE\ Wm^{-2}$	$RMSE\ Wm^{-2}$	t
5.41	18.74	1.0001

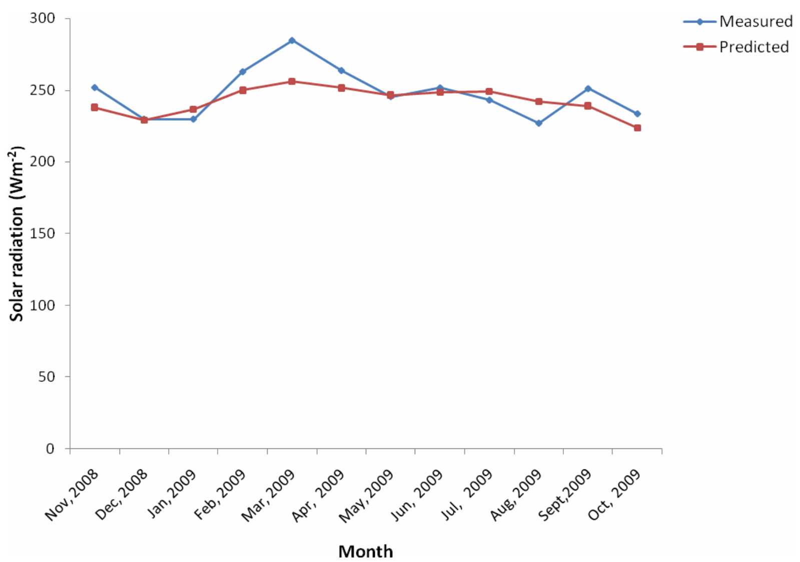

Figure 4: The Measured and Predicted Values of Solar Radiation for Maiduguri

Conclusion

The measurement and prediction of global solar radiation over Maiduguri were carried out in this work. The measurement was done with the aid of a constructed Reliable Model Pyranometer (RMP002) while the prediction was carried out using Angstrőm–Prescott theoretical model based on sunshine hour duration. The results obtained show a good agreement measured and predicted values of global solar radiation. The average RMSE and MBE for the comparison between measured and predicted global radiation are 18.74 and 5.41Wm^{-2}, respectively. These values are in the acceptable ranges. The calculated t-statistic value is about 1.0001, which is less than the critical t value (1.96).

This Constructed Reliable Model Pyranometers can then 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.

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