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# Comparative Studies of Measured and Estimated Values of Global Solar Radiation using a Constructed Reliable Model Pyranometer and Angstrőm-Prescott Model at Bauchi, Nigeria

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**ABSTRACT**

*In this study, Angstrőm – Prescott model was utilized for estimation of global solar radiation for Bauchi, Nigeria from sunshine hours. The estimated results obtained for twelve months, starting from 1st November, 2008 to 31st October, 2009 were compared to measured values obtained with a constructed reliable model pyranometer. The measurements were obtained within the same period.The values of the global solar radiation estimated and measured were tested using Mean Bias Error (MBE), Root Mean Square Error (RMSE), and the t-statistics. Average RMSE and MBE for comparison between measured and estimated global solar radiation were 43.60*$Wm^{-2}$ *and 12.59*$Wm^{-2}$*, respectively. The t-statistics was used as the best indicator; this indicator depends on both, and is more effective in determining the model's performance. The agreements between the estimated and measured data were remarkable.*

**Keywords:** Angstrőm-Prescott Model; Sunshine Hours; Reliable Model Pyranometer; t-statistics.

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## INTRODUCTION

Renewable energy is considered as a key source for the future, not only for Nigeria but also for theworld .This is primarily due to fact that renewable energy resources have some advantages ifcompared to fossil fuels .They are, in fact, complementary to each other and can be usedeffectively alone or in combinations of two or more renewable energy sources likewind andbiomass.

Global solar radiation is of economic importance as analternative renewable energy.It has a fundamental importance for life on earth.Obviously, the best solar radiation information is that obtained from experimental measurements of the global and diffuse components of the solar insolation at the location in question. Unfortunately, the measurements of this radiation are done only at a few places due to lack of measuring instruments. For this reason there have been attempts at estimating them from theoretical models. This correlations estimate the amounts of monthly average solar radiation from more readily available meteorological parameters such as the sunshine duration, extraterrestrial radiation etc.

Several researchers have determined the applicability of the Angstrőm type regression model for estimating global solar radiation [1-13].Accurate modeling depends on the quality and quantity of the measured data used and is a better tool for estimating the global solar radiation of location where measurements are not available.

The objective of this study is to present the measurement of solar radiation for Bauchi from a reliable model pyranometer we developed and correlated the values obtained from Angstrőm – Prescott model by using various statistical comparison methods such as MBE, RMSE and t-statistic. The need for radiation data covering entire areas led to the development of the Pyranometer.

**Instrumentation**

The instrument used for the measurement of solar radiation is a Reliable Model Pyranometer (RMP003) we developed (Figure 1). The pyranometer is shown as a circuit diagram in Figure 2.The transimpedance amplifier shown in Figure 3, configured around the LTC1051 operational amplifier (OPAM), was used for signal conditioning from the photodiode (see Figure .2). In this circuit $I_p$is the photocurrent from the diode and $C$ its parasitic capacitor. $C_c$, $R_c$and $C_r$are compensation, correction and stabilization elements respectively. Finally, $R_f$is the feedback resistor which fixes the DC gain in the circuit, so the output from this is $V_0= I_p R_f$.

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 $5088 \pm 0.027 Wm^{-2}$


**Figure 1:Picture of the Constructed Reliable Model Pyranometer undergoing Measurements**

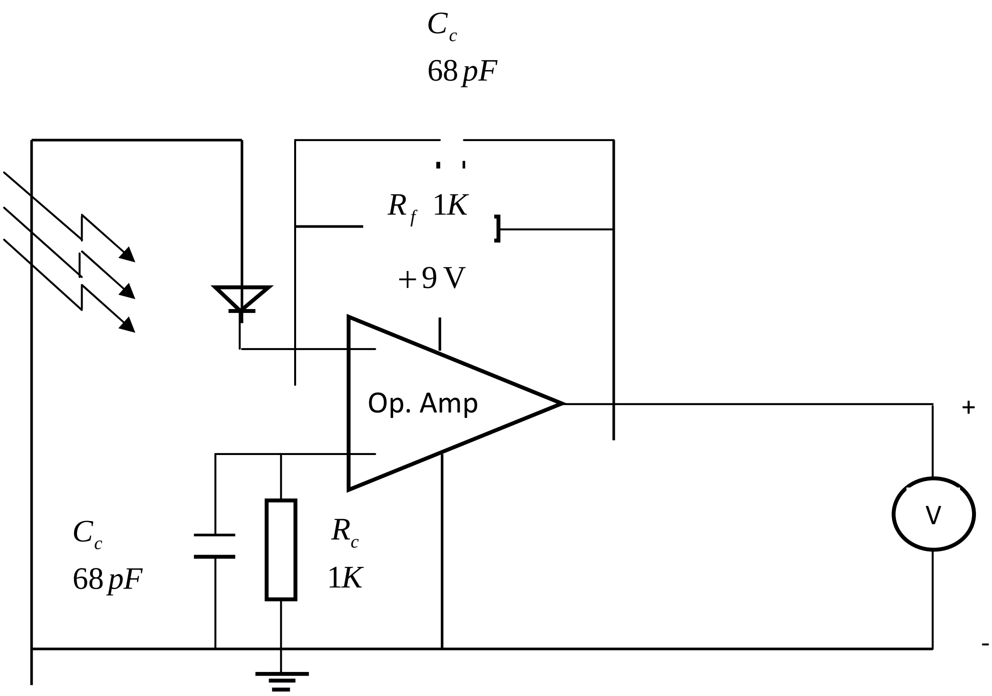


**Figure 2: Pyranometer circuit diagram**

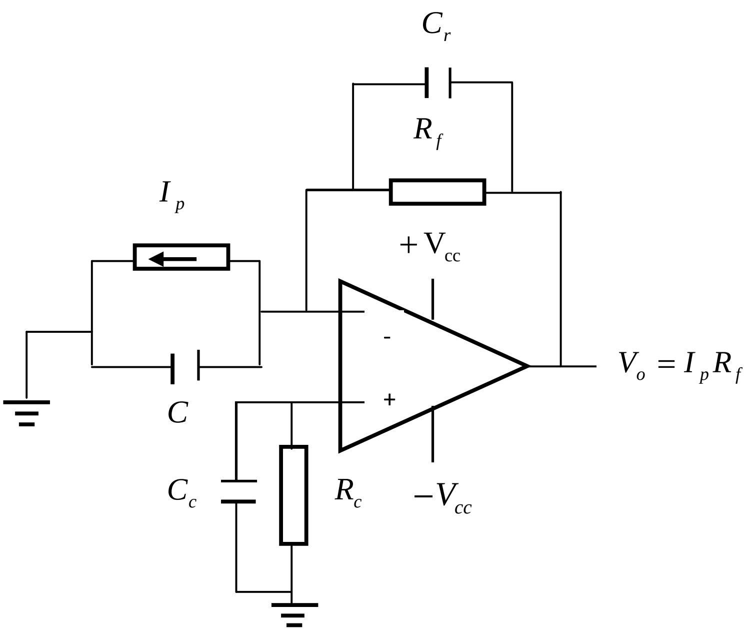


**Figure 3:Transimpedance amplifier to condition the $I_p$signal provided by the photodiode**

## Estimation Methods

Different climatic parameters have been used in developing empirical relations for predicting the monthly average global radiation. Among the existing correlations, the data of sunshine duration are widely available in many countries; various formulas based on them have been proposed to determine solar radiation from sunshine duration. The most generally used 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 [14]:

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

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 [15].

For monthly average, this formula holds [14]:

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

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 [16] and also confirmed by [17]

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

Whereas there are many methods to evaluate these constants.

The extraterrestrial solar radiation on a horizontal surface can be calculated from the following equation [14]:

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

The value of $1367\,Wm^{-2}$ has been recommended for solar constant $I_{sc}$ [18].
The hour angle $\omega_s$ for horizontal surface is given as [14]:

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

Declination is calculated as [19]:

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

Where $d_n$ 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 [14]:

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

(from equation (5)).

## Data and Methodology

The daily sunshine hour data were collected for a period of one year (from 1st November, 2008 to 31st October, 2009) from AbubakarTafawaBalewa University's meteorological station in Bauchi. The relevant meteorological and solar radiation data like $H$, $H_o$, $S/S_o$, $\omega$, $\delta$, $a$ and $b$ calculated from equations (1) – (7) are presented. The measurement of solar radiation at 1 minute intervals with the aid of the reliable model pyranometer was recorded for Bauchi, Nigeria, using a data logger betweenlatitudes $10^0 19'$ and longitude $9^0 50'$. 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. Monthly average value of solar radiation was then determined in $Wm^{-2}$.The global solar radiation data measured in ($MJm^{-2}day^{-1}$) was converted to ($Wm^{-2}$) using a factor of 11.6 $Wm^{-2}$ shown in Table1.

**Table 1: Conversion factors for radiation**

| | multiplier to obtain energy received on a unit surface per unit time | | | | equivalent evaporation |
|---|---|---|---|---|---|
| | MJ m$^{-2}$ day$^{-1}$ | J cm$^{-2}$ day$^{-1}$ | cal cm$^{-2}$ day$^{-1}$ | W m$^{-2}$ | mm day$^{-1}$ |
| 1 MJ m$^{-2}$ day$^{-1}$ | 1 | 100 | 23.9 | 11.6 | 0.408 |
| 1 cal cm$^{-2}$ day$^{-1}$ | 4.1868 x 10$^{-2}$ | 4.1868 | 1 | 0.485 | 0.0171 |
| 1 W m$^{-2}$ | 0.0864 | 8.64 | 2.06 | 1 | 0.035 |
| 1 mm day$^{-1}$ | 2.45 | 245 | 58.5 | 28.4 | 1 |

*(Source: http://www.fao.org/docrep)*

**Methods of Evaluation**

The performance of the RMP003 was evaluated in terms of the following statistical error tests: the mean percentage error (MPE), mean bias error (MBE), root mean square error (RMSE) and t – statistic. These error terms are calculated using the following equations:

$$MBE = \left[ \sum (\bar{H}_{i,meas} - \bar{H}_{i,est}) \right] / n \qquad (8)$$

$$RMSE = \left\{ \left[ \sum (\bar{H}_{i,meas} - \bar{H}_{i.est})^2 \right] / n \right\}^{1/2} \qquad (9)$$

$$MPE = \left\{ \sum \left[ (\bar{H}_{i,meas} - \bar{H}_{i,est}) / \bar{H}_{i,est} \right] x100 \right\} / n \qquad (10)$$

$$t = \left[ (n-1) MBE^2 / (RMSE^2 - MBE^2) \right]^{1/2} \qquad (11)$$

Where $\bar{H}_{i,est}$ and $\bar{H}_{i,meas}$ is the i$^{th}$ insolation estimated and measured respectively; and n is the total number of observations.

A zero value for MBE is ideal and alow RMSE is desirable. The RMSE test provides information on the short-term performance of the studied model as it allows a term – by – term comparism of the actual deviation between the measuredvalues and the calculated values. The MPE test gives long termperformance of the examined regression equations, a positive MPEvalues provide the averages amount of over-insolation in themeasured values, while the negative values gives under-insolation.A low value of MPE is desirable. The t-statistic is a new indicator of adjustment between calculated and measured data allowing the data to be compared and, at the same time, can induced whether or not data measurements are statistically significant at a particular confidence level.

## RESULTS AND DISCUSSION

The monthly mean daily solar radiation measured with RMP003 and estimated using Angstrőm – Prescott model are presented in Table 2 while Table 3 contains the Mean Bias Error (MBE), Root Mean Square Error (RMSE) and t – statistics.

It is possible to observe that the Angstrőm–Prescott coefficients show variations during the course of the year. Variations in a and b values are explained as a consequence of periodic climatological variations in the atmosphere. The overall mean values of $a$ and $b$ were, respectively, 0.27and 0.59. It is observed from the results that the maximum percentage error between the measured and predicted values of global radiation is 19.63%

**Table 2: Comparison between Estimated and Measured values of monthly average daily global radiation**

| *Month* | $\bar{S}/\bar{S}_o$ | *a* | *b* | $\bar{H}_o$ $MJm^{-2}d^{-1}$ | $\bar{H}$ Estimated $MJm^{-2}d^{-1}$ | $\bar{H}$ Estimated $Wm^{-2}$ | $\bar{H}$ Measuerd $Wm^{-2}$ | *MPE* % |
|---|---|---|---|---|---|---|---|---|
| Nov, 2008 | 0.72 | 0.35 | 0.41 | 31.31 | 20.20 | 234.32 | 265.60 | 13.35 |
| Dec, 2008 | 0.71 | 0.35 | 0.41 | 30.97 | 19.85 | 230.26 | 249.08 | 8.17 |
| Jan, 2009 | 0.72 | 0.35 | 0.41 | 32.96 | 21.27 | 246.73 | 257.07 | 4.19 |
| Feb, 2009 | 0.66 | 0.33 | 0.45 | 35.59 | 22.31 | 258.80 | 305.43 | 17.85 |
| Mar, 2009 | 0.60 | 0.31 | 0.49 | 37.61 | 22.72 | 263.55 | 315.29 | 19.63 |
| Apr, 2009 | 0.43 | 0.26 | 0.61 | 37.89 | 19.79 | 229.56 | 215.50 | -6.12 |
| May, 2009 | 0.29 | 0.21 | 0.70 | 37.26 | 15.39 | 178.51 | 177.43 | -0.61 |
| Jun, 2009 | 0.27 | 0.21 | 0.72 | 37.00 | 14.96 | 173.57 | 170.10 | -2.00 |
| Jul, 2009 | 0.24 | 0.20 | 0.74 | 37.39 | 14.12 | 163.77 | 160.86 | -1.78 |
| Aug, 2009 | 0.25 | 0.20 | 0.73 | 37.48 | 14.34 | 166.30 | 169.35 | 1.83 |
| Sept,2009 | 0.28 | 0.21 | 0.72 | 36.18 | 14.89 | 172.74 | 172.70 | -0.02 |
| Oct, 2009 | 0.27 | 0.21 | 0.72 | 33.57 | 13.58 | 157.48 | 168.22 | 6.82 |

**Table 3: Statistical Test Results**

| *MBE* $Wm^{-2}$ | *RMSE* $Wm^{-2}$ | *t* |
|---|---|---|
| 12.59 | 43.60 | 1.0 |

According to the statistical test results, the values of RMSE and MBE are in the acceptable ranges. As shown in Table 3 the values of RMSE and MBE are 43.60 $Wm^{-2}$ and 12.59 $Wm^{-2}$ respectively.

The variation of the daily global radiation measured and computed is represented in Figures 4. A fairly good agreement between measured and calculated global radiation for all months is clear. The percentage error for measurement for a single month never exceeds ± 19%; however, for the whole period is about 5.12%. The best month, March, with global solar radiation of 315.29 $Wm^{-2}$ and 263.55 $Wm^{-2}$ measured and estimated respectively, contributed 19.63% errors. The result also shows that the measured global solar radiation values for Bauchi during the rainy season is between 160.86 $Wm^{-2}$ and 169.35 $Wm^{-2}$ and the estimated values is between 163.77 $Wm^{-2}$ and

166.30 $Wm^{-2}$ with a percentage error of -1.78% and 1.83% respectively. As can be seen in Figure 4 the estimated values during most of the time arelower than the measured values by an amount of 1 to 19 %.

The comparison between the measurement and estimation was carried out according to the t value,because this statistic is more effective for determining the statistical properties. For all the whole period, the calculated t values was less than the critical t value (1.96).

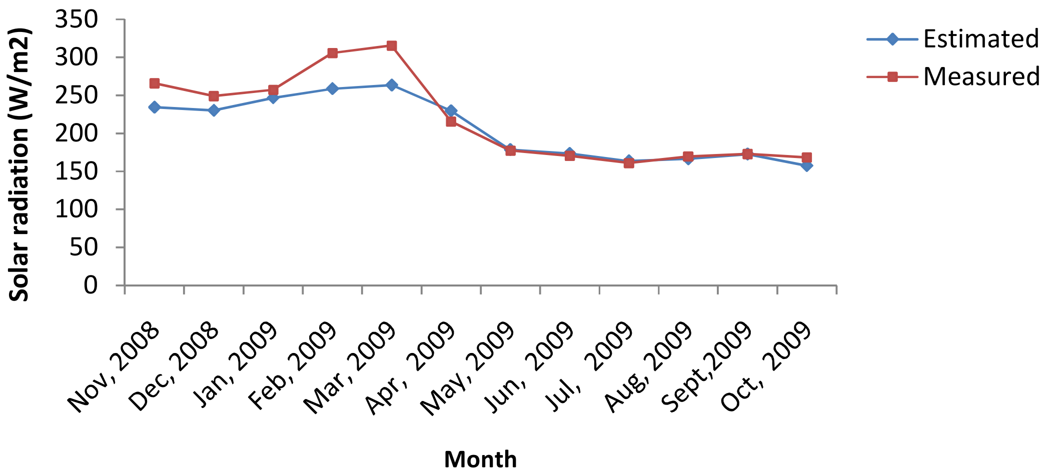


**Figure 4: The Measured and Estimated Values of Solar Radiation**

## CONCLUSION

The measurement and estimation of solar radiation using a constructed reliable model pyranometer and Angstrőm – Prescott model were presented and investigated. The results show a good agreement between estimated and measured values of monthly mean of daily global solar radiation.The statistical error tests reveal that average RMSE and MBE for the comparison between observed and estimated global radiation are 43.60 $Wm^{-2}$ and 12.59 $Wm^{-2}$, respectively. The t-statistic depends on both, the RMSE and MBE, and it was recommended that it should be used in conjunction with these indicators in order to help to assess a model's performance more reliably.

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