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Calibration of a Pyranometer using Regression Analysis

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***Abstract*— Pyranometers are vital when it comes to solar power. Pyranometers are sensors that give us the reading for Irradiance. The main problem with many pyranometers is that they are inaccurate at certain times given that the calibration performed by the manufacturing companies will be done on a hardware basis but can improve the accuracy further on a software basis using soft computing techniques like regression. The growing energy deficit in the world has created a wanting for renewable energy sources like solar power and solar power has to be estimated accurately as it helps grid engineers make important decisions like voltage control and frequency control that are vital to the stable working of a solar grid but if pyranometers give us inaccurate readings for irradiance, solar power won't be estimated accurately so in this paper, regression model is proposed that has improved the accuracy of a particular pyranometer.**

Keywords—pyranometer, solar power, regression

I. INTRODUCTION

Renewable Energy has gained prominence over the last decade and it is forecasted that renewable energy will play an important part in the future of Indian power generation plants [1].The vital reason for the increase in the focus on renewable energy is the rise of circular economy in industries like tourism [2].Circular Economy is a process used by the industry to produce no wastes by analyzing the entire life cycle of a product and recycling the waste products produced while manufacturing the product [3].One of the main ways the industries are turning to renewable energy is by generating solar energy using solar panels which has produced a meteoric growth in the renewable energy sector [4]. Irradiance is an important parameter when it comes to solar power [5]. It is therefore important to measure Irradiance accurately. Pyranometer is used to measure irradiance [6]. It is important to calibrate sensors to get accurate measurements. In the past literature, a low cost pyranometer was designed and it was tested along with a standard pyranometer. The error percentage for the low cost pyranometer was found and the calibration constant was added to the low cost sensor reading to get more accurate readings [7]. There is also another method where the influence of weather factors like air temperature, air mass etc. was accounted for to calculate irradiance accurately [8].

Regression is a useful tool when it comes to data analytics. In the past literature, regression was being used to forecast stock market, weather forecast numbers with the regression modelling being carried out using the past data sets [9]. Regression can also be used to generate more accurate data from faulty data. Regression can be basically classified into linear and non-linear regression. In the past literature, linear regression was used to improve the accuracy of a temperature sensor named DHT11.Readings of air temperature using DHT11 and thermometer were recorded simultaneously. The thermometer's readings were taken as standard readings. An equation was then established to relate the thermometer's readings and DHT11's readings using linear regression [10]. Linear regression was also used to increase the accuracy of K-Type Thermocouples for applications that require a lower temperature with the expensive oil bath temperature instrument used as reference [11]. Non-linear regression can also be used for calibration of sensors. Logarithmic CMOS image sensors have been calibrated in the past using non-linear regression where non-linear regression helped in removing noise from the Image sensor's output [12]. In the past, Regression has also been used for a smart irrigation system [13].

In this paper, the accuracy of a relatively cheap pyranometer have increased by setting an expensive industrial level pyranometer as reference for calibration purposes. Firstly, readings are recorded from both the expensive and the cheaper pyranometer simultaneously and then tried out various regression models such as linear, quadratic, cubic etc. for the recorded data and all of these regression models had only one input. The input was the cheaper pyranometers reading and the output was expected to be a more accurate reading for irradiance given that a more expensive pyranometers reading was set as reference for the output.

II. THEORETICAL BACKGROUND

A. *Sp-110 pyranometer*

Irradiance is defined as the amount of sunlight falling on a surface per unit area [6]. Irradiance is measured in measured in watts per square meter. Pyranometer is a sensor that measures the shortwave radiation on earth surface. There are various kinds of pyranometer available in the market. SP series pyranometer manufactured by Apogee Instruments are silicon based pyranometers that can capture close to 80% of the shortwave radiation but is calibrated to account for the entire solar spectrum. SP110 has a curved surface so from our observation the angle between the sun rays and the pyranometer is one of the major factors contributing towards the error therefore chosen a flat pyranometer namely SE1000-SEN-IRR-S1 for reference where the angle between the sun rays and the pyranometer won't be a major problem for error. There is still considerable amount of error that can be reduced using soft computing methods.

There are many pyranometers in the SP series namely SP-110, SP-230, SP-420 etc. SP-110 is lowest in terms of cost so chosen to improve the accuracy of SP-110's readings.

SP-110's readings come in the form of voltage values which can be read using a multimeter or by inserting the cables of the pyranometer into the analog pins of a microcontroller and are using an Arduino mega microcontroller where 5 V is by default mapped to a value of 1023 and 0 V is mapped to a value of 0. Multiply the voltage value by a factor of 5 to get the readings in W/m^{2}as 5 W/m^2 per mv is the calibration factor. The output range of SP-110 is in the range of 0 to 400 mv.

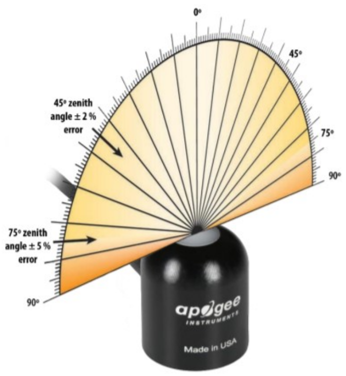

Fig. 1. Error variation for different angles between sunlight and the pyranometer (SP-110) (Source: Apogee Instruments SP-110 Owner's Manual, p. 8)

The error percentage varies for different angles of the pyranometer. As the angles between the radiation and the pyranometer increases, the error also increases. The maximum error is 10% which occurs when the angle between the sun's rays and the pyranometer is 90 degrees. Angle between the sun's rays and the pyranometer might just be one factor that accounts for the error of the sensor. There might be any other factors that contribute towards a larger error of the sensor's readings.

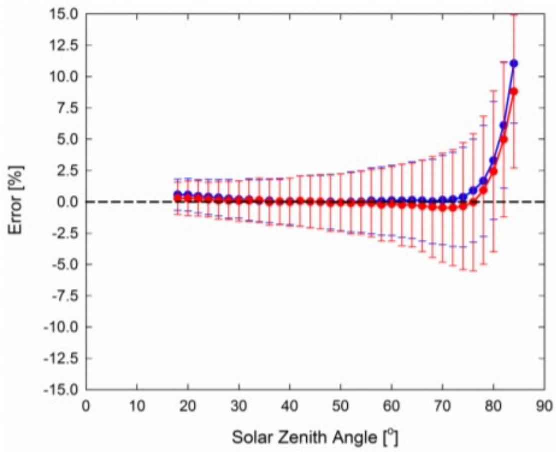

Fig. 2. Graph depicting the error variation at different zenith angles for SP-110 (Source: Source: Apogee Instruments SP-110 Owner's Manual, p. 8)

Apogee Instruments have calculated error percentages for different conditions and for Conifer canopy, the error percentage was found to be 19.2% whereas for deciduous canopy, the error percentage was found to be 16% and for Clear Sky, the error percentage was found to be 0% but, in our case, got some error percentages for clear sky conditions when compared SP-110 to an industrial level sensor.

B. SE1000-SEN-IRR-S1

The SE1000-SEN-IRR-S1 is a highly accurate pyranometer that is used mainly in the industries.SE1000-SEN-IRR-S1 has a maximum error percentage of 3% with output range of 0-1.5V with 1.5 V mapped to 1500 W/m^2 and 0V mapped to 0 W/m^2 .The output range of SEN1000-SEN-IRR-S1 is broader than that of SP-110.All these factors guarantees better readings for SE1000-SEN-IRR-S1 compared to SP-110. SE1000-SEN-IRR-S1 is used as reference given that this sensor is used in the power station in Kerala where took our readings for both SE1000-SEN-IRR-S1 and SP-110.

Fig. 3. SE1000-SEN-IRR-S1

C. Regrssion

Regression analysis is a statistical technique which is used in data analytics [9]. In regression analysis, an equation based is modelled on independent variables to predict a dependent variable where multiple independent variables are possible. Regression analysis basically helps us determine which equations fits most of the data points accurately and used regression analysis for calibration to improve the readings of SP110 to the standard of SE1000-SEN-IRR-S1 with the readings of SE1000-SEN-IRR-S1 being used as the datapoints to which the curve should fit. There are two types of regression

Linear Regression: This method is used in data analytics to determine the formula between two or more independent variables and the dependent output variable by finding the closest fit for the constants of a set of linear equations that are formed using the data for the independent variables. The relation between the dependent variable and independent variables is linear in the case of linear regression [11].

Non-Linear regression: Non-linear regression is a method of regression analysis in which data for the independent input variables are used to find the constants of a non-linear function and this non-linear function consists of a nonlinear combination of one or more independent input variables [12]. Quadratic and cubic equations functions are examples of non-linear functions.

III. PROPOSED METHORDOLOGY

The Figure 4 depicts the methodology that followed for our estimation.

Fig. 4. Proposed Flow of Methodology

The measurement of Irradiance from high quality industrial level sensor (SE1000-SEN-IRR-S1) and relatively less accurate sensor (SP-110 Pyranometer) was measured simultaneously with a constant time interval of 5 minutes for 3 consecutive days. A total of 864 data points were collected. with 70% of data being fed into Minitab software to find constants for various regression models and 30% of the data was kept for testing.

At first, the irradiance data from sensor SE1000-SEN-IRR-S1 and SP-110 were collected simultaneously with a constant time interval of 5 minutes. This data is then used to model an equation using regression.

The mean absolute accuracy for SP-110's readings was initially calculated which showed up to be 73.57 %, so the regression model has to be developed such that the mean absolute accuracy for the regression model is more than 73.57 %. Regression is used here to basically improve the readings of a relatively inaccurate sensor where the inaccurate readings ae given as input and got accurate readings as output with the more accurate sensor's readings as reference.

IV. RESULT

Initially, SP110 was 73.57% accurate when SE1000-SEN-IRR-S1's readings were taken as reference so our motive was to try various regression models to improve SP110's readings beyond % accuracy. The linear regression model was initially tried which showed an accuracy of 68.05%, because the data points ware saturating after a particular irradiance value, linear regression was not able to account for this saturation

Then moved on to non-linear regression models and tried models from quadratic to quintic. The quartic regression model gave the most improvement on SP-110's reading. The reason non-linear regression models work best for this case is because there are lot of variations between SP-110's readings and SE1000-SEN-IRR-S1 readings and linear models can't account for these variations.

A. Linear Regression Model:

$$Y = Ax + B \tag{1}$$

where
Y= SE1000-SEN-IRR-S1's reading
X= SP-110's reading
A=0.8794
B=52.6

So this linear regression model was tested using the test dataset [11]. The mean absolute accuracy was calculated as 68.05 % which is approximately 5.52% less accurate than the SP-110's readings.

B. Poisson regression models:

$$Y=\exp\ (A*x + B) \tag{2}$$

where
Y= SE1000-SEN-IRR-S1's reading
X= SP-110's reading
A= 0.001735
B= 5.2305

The Poisson distribution model was tested using the test dataset and the mean absolute accuracy was calculated as 74.35% which is approximately 0.78% more accurate than the SP-110's readings.

C. Non-linear quadratic regression model:

$$Y=A*x^2 + B*x + C \tag{3}$$

where
Y= SE1000-SEN-IRR-S1's reading
X= SP-110's reading
A= -0.000330802
B= 1.2354
C= -19.4817

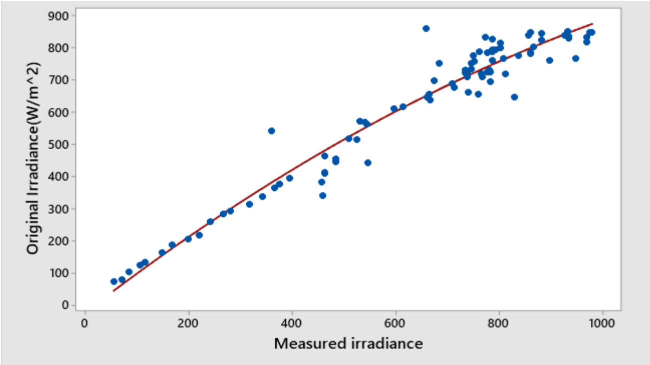

Fig 5: Fitted line plot of Non-Linear Quadratic Regression Model

This quadratic regression model's accuracy was calculated as 69.47%. This is approximately 4% less than SP-110's accuracy.

D. Non-linear quintic regression model:

$$Y=A*x^5 + B*x^4 + C*x^3 + D*x^2 + E*x + F \qquad (4)$$

where
Y= SE1000-SEN-IRR-S1's reading
X= SP-110's reading
A= $8.13174*10^{-12}$
B= $-2.33483*10^{-06}$
C= $2.36207*10^{-05}$
D= -0.0102406
E= 2.74783

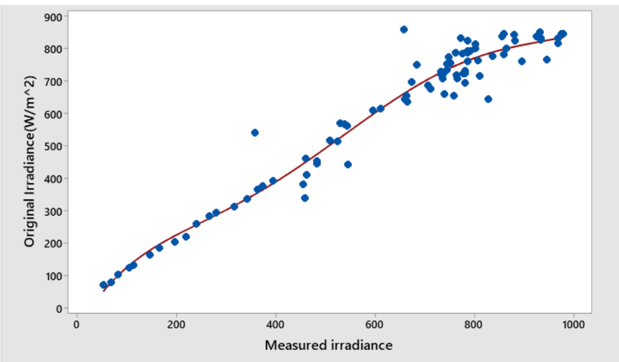

Fig 6: Fitting line plot of Non-Linear Quintic Regression Model

In this quintic model, the mean absolute accuracy was calculated as 72.18%. This quintic regression model is 1.39% more accurate than SP-110's readings.

E. Non-linear regression model(order of 5):

$$Y=A*x^5 + B*x^3 + C*x + D \qquad (5)$$

where
Y= SE1000-SEN-IRR-S1's reading
X= SP-110's reading
A= $-4.91421*10^{-13}$
B= $4.24942*10^{-07}$
C= 0.848954
D= 36.4319

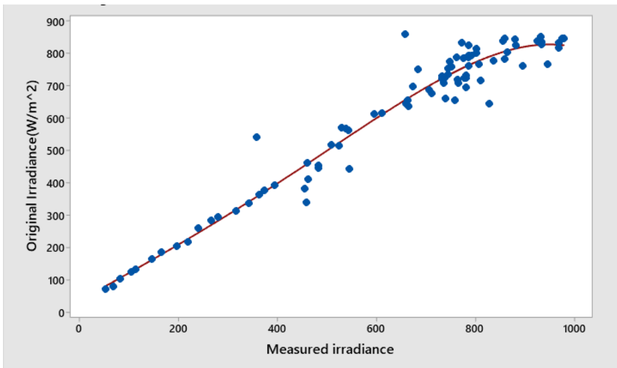

Fig 7: Fitting line plot of Non-Linear Regression Model (order of 5)

In this nonlinear model, the mean absolute accuracy was calculated as 77.83%. This regression model has improved its accuracy over SP-110 by 4.26%.

F. Non-linear regression model(indefinite power):

$$Y=A*x^B \qquad (6)$$

where
Y= SE1000-SEN-IRR-S1's reading
X= SP-110's reading
A= 2.4705
B= 0.856048

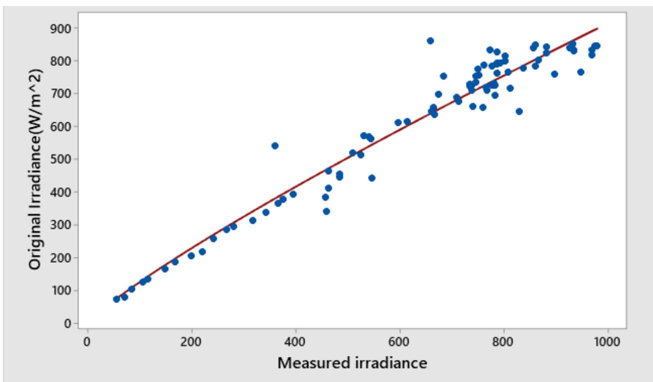

Fig 8: Fitting line plot of Non-Linear Regression Model (indefinite power)

In this non liner model, the mean absolute accuracy was calculated as 77.74%. This method is 4.17% more accurate than SP-110's readings.

G. Non-linear regression model(order of a constant):

$$Y=A*x^B + C \quad (7)$$

where
Y= SE1000-SEN-IRR-S1's reading
X= SP-110's reading
A= 5.05805
B= 0.856048
C= -60.24

In this nonlinear model, the mean absolute accuracy was calculated as 70.45%. This is approximately 3.12% less than SP-110's accuracy.

The below tabulation 1 is a summary of all the above regression models that have been tested to improve the accuracy of the sensor.
The mean accuracy of each regression model was calculated as

$$\text{Mean Accuracy}=\sum (100-((ABS(M-N)/N)*100)) \quad (8)$$

M= Irradiance calculated by regression model
N= Irradiance reading of SE1000-SEN-IRR-S1

The mean accuracy of SP110 was calculated as

$$\text{Mean Accuracy}=\sum (100-((ABS(P-N)/N)*100) \quad (9)$$

P= Irradiance of SP-110 Pyranometer
N= Irradiance reading of SE1000-SEN-IRR-S1

The improvement is the difference between accuracy of calculated regression model and SP110's readings.

Table 1. Summary of all the Regression Models.

S. N0	Regression	Accuracy	Improvement
1	$Y = 0.8794x + 52.6$	68.05%	NIL
2	$Y= \exp(0.001735*x + 5.2305)$	74.35%	0.71%
3	$Y= -0.000330802*x^2 + 1.2354*x - 19.4817$	69.47%	NIL
4	$Y= -1.97377*10^{-9}*x^4 + 3.16771*10^{-6}*x^3 - 0.00163405*x^2 + 1.24541*x + 9.33716$	79.04%	5.47%
5	$Y=2.4705*x^{0.856048}$	77.74%	4.17%
6	$Y= -4.91421*10^{-13}*x^5 + 4.24942*10^{07}*x^3 + 0.848954*x + 36.4319$	77.83%	4.26%
7	$Y=5.05805*x^{0.856048} - 60.24$	70.45%	NIL

Y= SE1000-SEN-IRR-S1's reading
X= SP-110's reading

In the summary of all the regression model experimented in MINITAB, $Y=A*x^4 + B*x^3 + C*x^2 + D*x + E$ is the best nonlinear regression model which achieves an improvement of 5.47%.

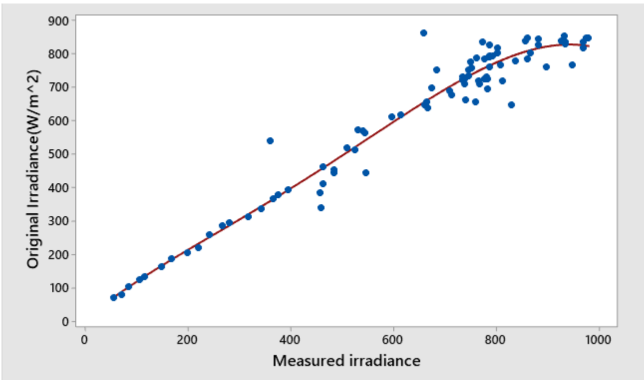

Fig 8: Fitting line plot of Non-Linear Quartic Regression Model

V. CONSLUSION

Regression can thus be performed for calibrating sensors as in our case a non-linear regression model namely the quartic model gave us the biggest improvement of 5.47 % in the accuracy of the pyranometer's readings. The second biggest improvement of 4.17% was given by the quintic model whereas linear model did not give us any improvement in the accuracy of SP110's readings therefore proved that non-linear model works best for calibration purposes especially in our case as irradiance is a weather factor and weather factors behave with unpredictability and that much amount of unpredictability can only be tackled by non-linear regression. Our study also proves that regression can be used to calibrate other sensors like ultrasonic sensor, light intensity sensor, infrared sensor etc. The same flow of methodology can be followed for any other sensor as this will help us understand which degree model is functioning properly for a particular sensor. This will be of use to companies who are looking to reduce the cost on purchasing sensors as they can purchase relatively cheap sensors and still get good readings from those sensors.

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