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A Study on Environmental Sensors for Low-Cost Weather Stations

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Abstract. Designing a low-cost weather station requires careful consideration of the selection of sensors used. The use of inappropriate or poorly calibrated sensors can result in inaccurate data acquisition, which ultimately affects the quality of weather observations. This paper conducts a literature study related to sensors that are often used in low-cost weather stations. Based on the study results, the most frequently monitored quantities are temperature, humidity, and atmospheric pressure. To demonstrate the calibration analysis of weather sensors, tests were conducted on the BME280 sensor, which is widely used to measure these three parameters. This test was conducted at a meteorological calibration laboratory that has been certified by the National Accreditation Committee (KAN). The test was carried out by building a sensor node equipped with a reference sensor, so that the test could be carried out simultaneously and at the same time. This aims to ensure that the BME280 sensor readings can be compared directly with the calibrated reference sensor, so that the accuracy and precision of the sensor can be evaluated more comprehensively. In this test, the BME280 sensor was tested before and after adjustment. The initial calibration results showed a deviation in pressure and temperature readings that exceeded the specified tolerance limits. After the adjustment process, the BME280 sensor showed a significant improvement in accuracy, with readings that were more consistent and closer to recognized measurement standards.

Introduction

An automatic weather station (AWS) is a device designed to measure various physical parameters of the environment, such as temperature, humidity, atmospheric pressure, wind speed, wind direction, light intensity, and precipitation[1]. These seven parameters are generally considered the standard elements that an AWS must have. The data obtained from these sensors is essential for monitoring weather conditions in real-time, which is useful in various applications.

However, in application, not all AWSs need to be equipped with all these parameters. Sometimes, a weather monitoring system only requires a few sensors depending on its specific needs. For example, weather stations in agricultural areas may focus more on rainfall and soil moisture parameters[2], [3], [4], [5], [6] while stations in urban areas may pay more attention to air pollution[7] and sunlight intensity parameters[8], [9]. This flexibility in sensor selection enables the development of more cost-efficient AWS systems, without compromising on key functionality.

Research also shows that many small-scale AWS system developments are designed with budget constraints in mind. Researchers often design weather stations using only those sensors that are relevant to their research objectives or focus, thus keeping costs down without compromising the accuracy of the data generated. With this modular approach, AWS can be customized for various specific applications, enabling more economical yet reliable weather monitoring.

Modern weather station applications play a vital role in various sectors of life, especially in the face of the challenges of climate change and extreme weather. With the ability to provide real-time and accurate weather data, these systems offer invaluable solutions to industries such as aviation, agriculture, shipping, and road transportation. In the energy sector, weather data is used to optimize electricity distribution and management of renewable energy sources. In addition, disaster management[10], [11], defense, tourism, and outdoor activities such as mountaineering[12] and sports also rely heavily on reliable weather information. Thus, weather station applications not only improve operational efficiency, but also contribute to public safety and better decision-making in various fields.

Many researchers and journals that focus on developing low-cost weather sensors often do not conduct adequate laboratory testing, especially regarding the sensor calibration process. This is a serious concern as poorly calibrated sensors have the potential to produce inaccurate data, which in turn can affect the quality of weather monitoring results. Although the use of affordable sensors offers an economical and efficient solution, without proper calibration testing, the reliability of the resulting data remains in doubt. Calibration conducted in a laboratory environment allows these sensors to be tested under controlled and precisely measurable conditions, thus ensuring that they meet certain accuracy standards. Calibration testing is therefore a very important step to guarantee sensor performance, especially when used in applications that require a high level of precision, such as in meteorology, agriculture and disaster management.

Methodology

Literature Study

Table 1 presents the results of a literature review on the use of different types and types of sensors applied in research on low-cost weather stations. Although this table provides a comprehensive overview of the sensor options used to measure weather parameters such as temperature, humidity, air pressure, and wind speed and other quantities.

Table 1. literature study on the use of sensors in the creation of low-cost weather stations.

Environmental sensors	Sensor components	Papers
Temperatur	LM35	(Radhi and Al-Naima, 2022)[13], (Heng et al., 2022)[14]
	BME280	(Shaw, 2024)[1], (Bernardes et al., 2023)[10], (Suparta et al., 2021)[15]
	DHT11	(Qasim et al., 2024)[8], (Gaikwad et al., 2023)[16], (Sakthi et al., 2023)[17], (Khuzairi et al., 2023)[18], (Paulraj et al., 2023)[19], (Chakraborty et al., 2023)[20], (Anik et al., 2022)[21], (Akilan et al., 2022)[4], (Wulandari et al., 2021)[22], (A. Gupta et al., 2021)[9], (Asanza et al., 2021)[23], (Mayurappriyan et al., 2021)[24], (Shevchenko et al., 2020)[25], (Bin Shahadat et al., 2020)[26]
	DS18B20	(Ali et al., 2024)[3], (Helal et al., 2022)[27]
	DHT22	(Stoyanov et al., 2024)[28], (Zhang et al., 2023)[29], (Tandan et al., 2022)[30], (Leon et al., 2021)[12]
	AHT20	(Haris et al., 2023)[7]
	HDC1080	(Priambodo and Nugroho, 2021)[31]
	SHT10	(Ioannou et al., 2021)[32]
	other sensors	(Khan et al., 2024)[2]
Humidity	BME280	(Shaw, 2024)[1], (Ali et al., 2024)[3], (Bernardes et al., 2023)[10], (Suparta et al., 2021)[15]
	DHT22	(Stoyanov et al., 2024), (Zhang et al., 2023), (Tandan et al., 2022), (Ioannou et al., 2021), (Leon et al., 2021)[12]
	DHT11	(Qasim et al., 2024)[8], (Gaikwad et al., 2023)[16], (Sakthi et al., 2023), (Khuzairi et al., 2023), (Paulraj et al., 2023), (Chakraborty et al., 2023), (Radhi and Al-Naima, 2022), (Anik et al., 2022)[21],

Environmental sensors	Sensor components	Papers
		(Heng et al., 2022)[14], (Akilan et al., 2022), (Wulandari et al., 2021), (A. Gupta et al., 2021), (Asanza et al., 2021), (Mayurappriyan et al., 2021), (Shevchenko et al., 2020), (Bin Shahadat et al., 2020)
	HDC1080	(Priambodo and Nugroho, 2021)
	other humidity sensors	(Khan et al., 2024)
Barometric Pressure	BMP180	(Qasim et al., 2024), (Zhang et al., 2023), (Gaikwad et al., 2023), (Sakthi et al., 2023), (Anik et al., 2022), (Akilan et al., 2022), (Wulandari et al., 2021), (Ioannou et al., 2021), (Leon et al., 2021), (A. Gupta et al., 2021), (Mayurappriyan et al., 2021), (Bin Shahadat et al., 2020)[26]
	BMP280	(R. Gupta et al., 2023)[33]
	DSP310	(Haris et al., 2023)[7]
	BME280	(Stoyanov et al., 2024), (Shaw, 2024)[1], (Bernardes et al., 2023), (Suparta et al., 2021)
	other barometric pressure sensors	(Khan et al., 2024)[2], (Heng et al., 2022)[14]
Wind Speed	Anemometer	(Ali et al., 2024)[3], (Khan et al., 2024)[2], (Stoyanov et al., 2024)[28], (Shaw, 2024), (Zhang et al., 2023)[29], (Bernardes et al., 2023)[10], (Haris et al., 2023)[7], (Henget al., 2022)[14], (Ioannou et al., 2021)[32], (Mathur et al., 2021)[34], (Mayurappriyan et al., 2021)[24]
Wind Direction	Davis 6410	(Ali et al., 2024)[3]
	Wind Direction WM30	(Heng et al., 2022)[14]
	wind vane WH-SP-WD	(Stoyanov et al., 2024)[28]
	other wind vane sensors	(Khan et al., 2024)[2], (Zhang et al., 2023)[29], (Bernardes et al., 2023)[10], (Haris et al., 2023)[7], (Radhi and Al-Naima, 2022)[13], (Ioannou et al., 2021)[32], (Mathur et al., 2021)[34], (Mayurappriyan et al., 2021)[24]
Rain Gauge	Davis 0.2mm	(Ali et al., 2024)[3]
	tipping bucket	(Stoyanov et al., 2024)[28], (Shaw, 2024)[1]
	pluviometer	(Bernardes et al., 2023)bernar[10]
	other rain gauge sensors	(Khan et al., 2024)[2], (Zhang et al., 2023)[29], (Haris et al., 2023)[7], (Ioannou et al., 2021)[32], (Mathur et al., 2021)[34]
Light intensity sensor	LDR	(Shaw, 2024)[1], (Qasim et al., 2024)[8], (Sakthi et al., 2023)[17], (Khuzairi et al., 2023)[18], (Akilan et al., 2022)[4], (A. Gupta et al., 2021)[9], (Asanza et al., 2021)[23], (Shevchenko et al., 2020)[25]
	BH1750	(Helal et al., 2022)[27]
Air quality sensor	VOC 2.5	
	MQ2	(Chakraborty et al., 2023)[20], (Heng et al., 2022)[14]
	MQ135	(Chakraborty et al., 2023)[20], (Tandan et al., 2022)[30]
	Other air quality sensors	(Khan et al., 2024)[2], (Sakthi et al., 2023)[17], (Haris et al., 2023)[7]
PH Meter	other sensors	(Zhang et al., 2023)[29]
Rain drop	FC-37	(Gaikwad et al., 2023)[16], (Anik et al., 2022)[21], (Wulandari et al., 2021)[22], (Asanza et al., 2021)[23]
	other Rain drop sensors	(Qasim et al., 2024)[8], (Sakthi et al., 2023)[17], (Khuzairi et al., 2023)[18], (Paulraj et al., 2023)[19], (Chakraborty et al., 2023)[20], (Radhi and Al-Naima, 2022)[13], (A. Gupta et al., 2021)[9]
Ultraviolet	GYM8511	(Qasim et al., 2024)[8], (A. Gupta et al., 2021)[9]
	other Ultraviolet sensors	(Shevchenko et al., 2020)[25]
Moisture soil	FC-28	(Stoyanov et al., 2024)[28], (Asanza et al., 2021)[23]
	other moister soil sensors	(Ioannou et al., 2021)[32]

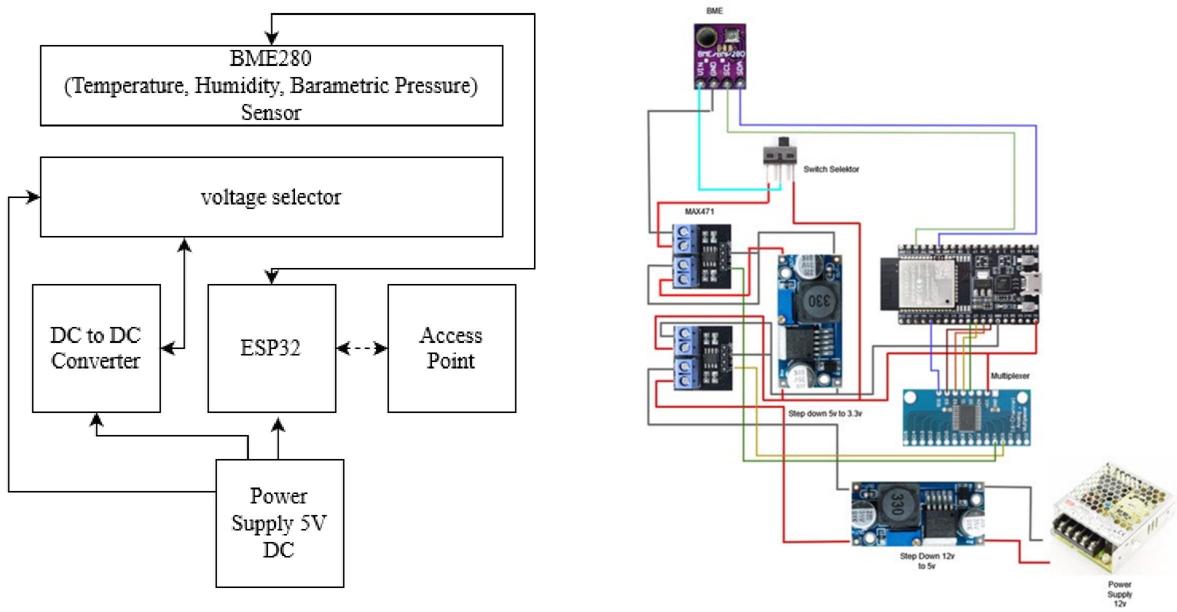
In the results of table 1, the literature study on physical quantities used in the construction of low-cost weather stations shows that in addition to commonly measured quantities such as temperature, humidity, air pressure, wind speed, wind direction, rainfall, and light intensity, there are also developments that involve the measurement of other quantities that are not always standard in conventional weather stations. Some studies integrate sensors to measure additional parameters such as air quality, which includes measuring the concentration of particulates (PM2.5, PM10) or gases such as CO2 and ozone, to monitor air pollution that can affect environmental and health conditions. UV sensors are also added to some systems to measure the intensity of ultraviolet light, which is important in the context of public health related to sun exposure. In addition, there are weather stations equipped with soil sensors, such as soil moisture and temperature sensors, which are especially useful in agricultural applications or environmental studies. Thus, the literature review shows that although low-cost weather stations usually monitor standard weather parameters, many developments try to add other physical quantities according to the specific needs of the application or research, thus expanding the scope and benefits of the monitoring system.

However, there are significant shortcomings in many of these studies, with most not conducting an in-depth analysis of sensor accuracy and precision according to standards set by the World Meteorological Organization (WMO). Meeting these standards is important to ensure the quality and reliability of the weather data produced. Without verification against these accuracy standards, there is the potential that the data generated by these low-cost weather stations is not fully valid, especially for applications where high accuracy is required, such as in weather prediction or climate change monitoring.

Design of Experimental Kits for Calibration

The BME280 sensor is becoming one of the most widely used components in the creation of low-cost weather stations due to its multifunctional capabilities, measuring temperature, humidity, and atmospheric pressure in a single device. Not only does this sensor offer an affordable price, but it is also easy to integrate with popular microcontrollers such as Arduino, Raspberry Pi, and ESP8266, making it a top choice in various DIY and research projects. Its low power efficiency and compact size further strengthen its position as a key component for cost-effective weather stations. However, it is important to emphasize that while these sensors offer good accuracy, a calibration process is necessary to ensure the reliability of the data generated. Without proper calibration, the measurement results from these sensors can suffer from deviations, especially over longer periods of time or under extreme environmental conditions. Therefore, regular calibration is necessary to keep the weather data generated accurate and reliable, especially when used for more sensitive applications such as precision agriculture or environmental monitoring. Good calibration will ensure that the use of the BME280 sensor, despite its low cost, still provides optimal and accurate performance in accordance with weather monitoring standards.

In figure 1 is a sensor node block diagram that illustrates how the system works. There is an ESP32 V4 as a microcontroller, a voltage source of 12 volt, a DC to DC converter to reduce the voltage from 12 volt to 5 volt and from 5 volt to 3.3 volts. There are BME280 sensors for temperature sensors, humidity sensors and atmospheric pressure sensors. Before the voltage enters the sensor on the sensor node, it will pass first, namely the voltage selector, choosing what voltage will be used for the sensors, either 5 volt or 3.3 volt voltage. The sensor uses a digital data pin using the I2C communication protocol. All input from the sensor will be processed by the EP32 microcontroller to read and process the data received by the data readings from the sensors which will then be sent to data processing using a local access point network.



(a) (b)

Fig. 1. (a) Diagram sensor node (b) Skematik sensor node.

Figure 2 displays the data acquisition architecture designed to operate on a local computer as a central server. In this system, the installed applications include an MQTT server, which serves as a broker to manage and host data sent from sensor nodes. This MQTT server is in charge of receiving messages from various sensors scattered in the field and ensuring that the data can be processed properly without any loss or delay. In the next layer, the API built using the Node-Red platform acts as a link between the data received by the MQTT broker and the InfluxDB database, which is used to store the acquired data in an efficient and structured manner. Node-Red simplifies data flow through visual integration that enables real-time data processing, while allowing users to monitor the data flow directly.

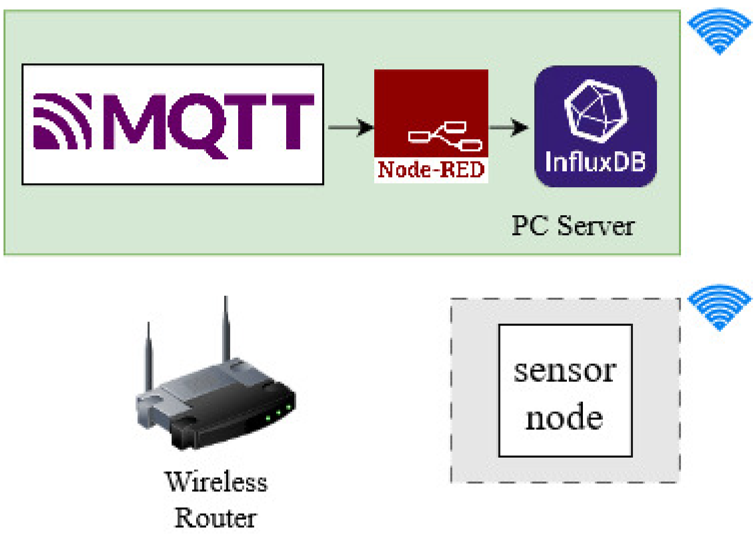


Fig. 2. Data acquisition architecture for calibration.

Result and Discussion

Meteorological equipment condition requirements follow the regulations set by World Meteorological Organization (WMO) (WMO, 2018)[35]. The tolerances of measurements that meet the requirements are presented in table 2. The table shows the tolerances of 3 physical quantities that will be tested using the BME280 sensor.

Table 2. Condition requirements for meteorological equipment by WMO.

No.	Parameters	Measurement range	Desired tolerance	Tolerance allowed
1	Air temperature	-80 ~ 60 ºC	0.3 °C for ≤ –40 °C 0.1 °C for > –40 °C and ≤ 40 °C 0.3 °C for > 40 °C	0.2 °C
2	Relative humidity	0 ~ 100%	1%	3%
3	Atmospheric pressure	500 ~ 1080 hPa	0.1 hPa	0.15 hPa

Five repetitions of calibration were performed for each quantity. The results of the analysis are shown in each subsection below.

BME280 Temperature Sensor Calibration.

Table 3 shows the accuracy and precision of the BME280 temperature sensor at each test point before adjustments are made. The lowest precision value is 98.76%, while the highest reaches 99.79%, with a median value of 99.33%. For accuracy, the lowest value is 96.90% and the highest is 99.63%, with a median value of 98.98%. In addition, precision and accuracy calculations were also performed for five calibration data at each test point. As a result, the lowest precision value is 98.00%, the highest value is 99.04%, and the median value is 98.29%. Meanwhile, the lowest accuracy is 97.25%, the highest value is 99.04%, and the median value is 98.29%.

Table 3. Accuracy and Precision of BME280 temperature sensor at each test point before adjustment.

Measurement point ($°C$)	1st Calibration		2nd calibration		3rd calibration		4th calibration		5th calibration		All five calibration data	
	PR (%)	ACC (%)	PR (%)	ACC (%)	PR (%)	ACC (%)	PR (%)	ACC (%)	PR (%)	ACC (%)	PR (%)	ACC (%)
20	99.7	99.5	99.1	97.3	99	97.3	98.8	96.9	99.2	97.9	98.6	97.3
25	99.5	99.4	99.3	98.4	99.3	98.4	98.8	97.8	99.1	98.3	99.1	98.3
30	99.7	99.5	99.2	98.8	99.6	99	99.8	99	99.1	98.5	99.3	98.8
35	99.7	99.6	99.4	99	99.5	99.4	99.1	98.7	99.5	99	99.3	99
40	99.6	99.6	99.3	99.2	99.3	99.1	99.5	99.5	99.4	97.9	98	97.7

note: PR (Precision), ACC (Accuracy)

Although it has the best accuracy value of 99.63%, the result of the bias value still exceeds the tolerance value allowed by WMO. Table 4 shows the bias value of the calibration data. The average correction value is 0.14 where the allowable tolerance is 0.2. This shows that the correction value obtained has met the requirements. However, adjustments will still be made to improve its accuracy.

Table 4. Bias of BME280 Temperature Sensor at each test point before adjustment.

Measurement point ($°C$)	1st calibration bias	2nd calibration bias	3rd calibration bias	4th calibration bias	5th calibration bias	Overall bias of the measurement range
20	0.04	0.37	0.32	0.37	0.27	0.27
25	0.02	0.23	0.25	0.24	0.20	0.19
30	0.06	0.13	0.18	0.22	0.19	0.16
35	0.02	0.12	0.03	0.13	0.16	0.09
40	0.01	0.04	0.08	0.02	0.61	0.11

To determine the range of values around a measurement that includes variability or uncertainty in the data, an error band graph is created. In the context of calibration and measurement, the error band provides information on how far the measurement result can vary from the true or reference value. Figure 3 shows the error band of the BME 280 pressure sensor. The error band value is obtained from the largest deviation between the measurement values of the standard measuring instrument and the test measuring instrument. In the temperature sensor calibration, the largest deviation is ±0.61.

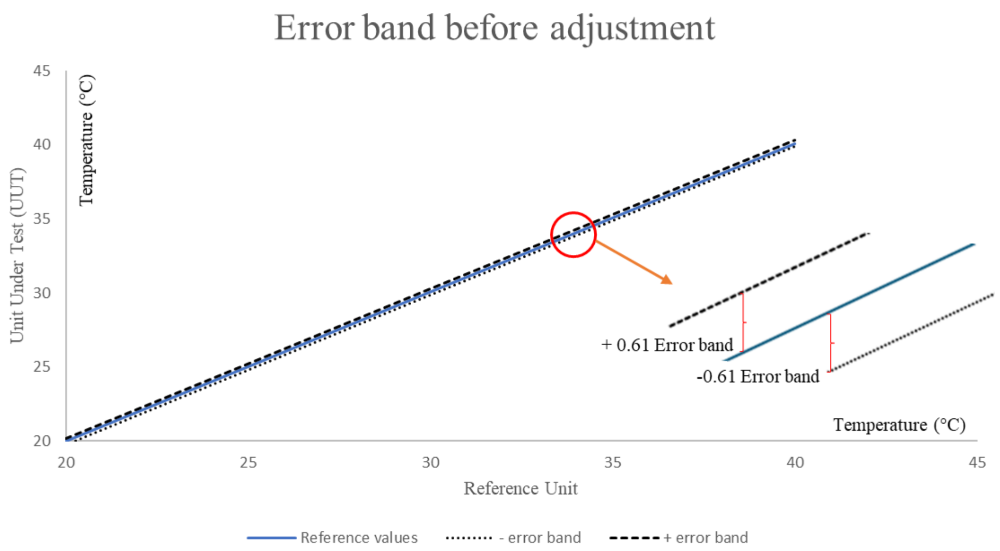


Fig. 3. Error Band on BME 280 temperature sensor before adjustment.

To improve the bias and accuracy values, a linear graph was found between the measurement values of the reference unit and the tested unit. Figure 4 shows the linear correlation between the reference unit measurement and the test unit measurement for the first calibration data. The same process was performed to obtain the linear correlation of the second to fifth calibration data, as well as for the combination of the five calibration data. In table 5, we can see the linear function and the coefficient of determination obtained. A coefficient of determination of 0.99 was achieved for the fifth calibration, while in the other calibrations it reached 1, indicating that the linear regression model obtained was able to explain the entire variation in the data very well.

Table 5. Linear correlation of reference unit temperature measurement with test unit.

Calibration data to	Linear function	R^2
1	y = 0.9982x + 0.1151	1.00
2	y = 0.9816x + 0.7443	1.00
3	y = 0.9857x + 0.6298	1.00
4	y = 0.9833x + 0.7249	1.00
5	y = 0.9642x + 1.1489	0.99
1,2,3,4,5	y = 0.9825x + 0.6742	0.99

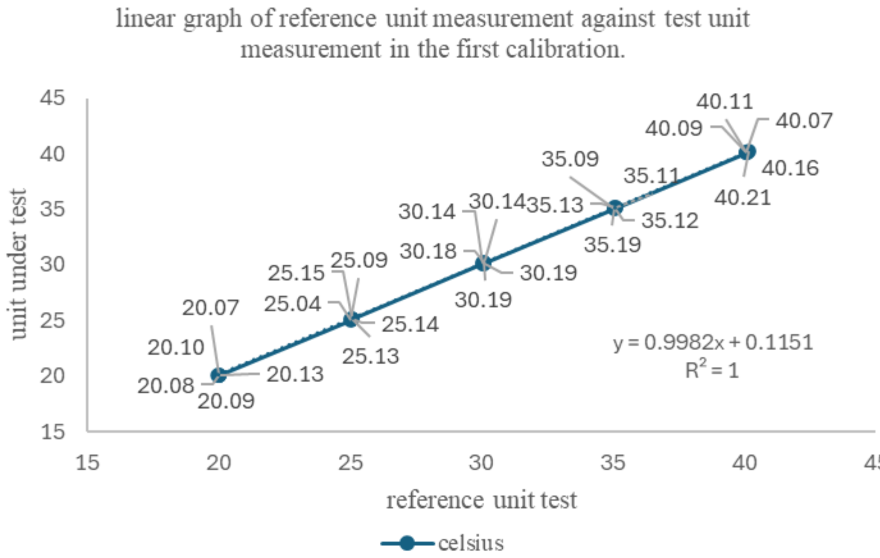


Fig. 4. Linear correlation of temperature measurement between reference unit and test unit.

The precision and accuracy results after tuning are shown in table 6, where the smallest precision value is 98.74%, the largest is 99.76%, and the median value is 99.34%. Meanwhile, the smallest accuracy value was 98.29%, the largest was 99.74%, and the median value was 99.20%.

Table 6. Accuracy and precision of the BME280 temperature sensor at each test point after adjustment.

Measurement Point (°C)	1st Calibration		2nd calibration		3rd calibration		4th calibration		5th calibration		All five Calibration data	
	PR (%)	ACC (%)	PR (%)	ACC (%)	PR (%)	ACC (%)	PR (%)	ACC (%)	PR (%)	ACC (%)	PR (%)	ACC (%)
20	99.7	99.5	99.1	99.1	98.9	98.8	98.7	98.6	99.2	98.3	98.7	98.5
25	99.5	99.3	99.3	99	99.3	99.2	99.7	99.6	99.1	98.9	99.1	98.9
30	99.7	99.7	99.2	99	99.6	99.5	99.8	99.7	99.1	98.7	99.1	99
35	99.7	99.6	99.4	99.3	99.5	99.2	99.1	99	99.4	98.6	98.7	98.7
40	99.6	99.5	99.3	99.2	99.3	99.2	99.5	99.4	99.3	98.5	98.9	98.7

note: PR (Precision), ACC (Accuracy)

The correction values after tuning show improvement in each calibration data. Table 7 displays the correction values obtained. The average correction value after tuning is 0.03, which meets the tolerance allowed by the World Meteorological Organization (WMO). Thus, it can be stated that the tuning results successfully improved the accuracy values. The error band value has improved after adjusting the sensor. The band error obtained after tuning is ±0.33.

Table 7. Bias of BME280 Temperature Sensor at each test point after adjustment.

Measurement point ($°C$)	1st calibration bias	2nd calibration bias	3rd calibration bias	4th calibration bias	5th calibration bias	Overall bias of the measurement range
20	0.04	0.01	0.02	0.02	0.17	0.05
25	0.05	0.06	0.03	0.03	0.05	0.04
30	0.00	0.06	0.02	0.01	-0.12	-0.01
35	0.03	-0.03	0.10	0.01	-0.28	-0.03
40	0.04	0.05	-0.02	0.04	0.33	0.09

BME280 Humidity Sensor Calibration

Table 8 shows the accuracy and precision of the BME280 humidity sensor at each test point before adjustment. The smallest precision value is 97.69% and the largest is 99.87%, with a center value of 99.55%. Meanwhile, the smallest accuracy was 92.27% and the largest was 98.7%, with a median value of 95.42%. Precision and accuracy calculations were also performed from a combination of five calibration data at each point. As a result, the smallest precision value is 97.92%, the largest is 98.63%, with a median value of 98.06%. Meanwhile, the smallest accuracy is 91.86%, the largest is 96.81%, and the median value is 94.21%. Although the best accuracy value reaches 98.7%, the correction results still exceed the tolerance limit allowed by the WMO.

Table 8. Accuracy and Precision of BME280 humidity sensor at each test point before adjustment.

Measurement Point (RH%)	1st Calibration		2nd calibration		3rd calibration		4th calibration		5th calibration		All five Calibration data	
	PR (%)	ACC (%)	PR (%)	ACC (%)	PR (%)	ACC (%)	PR (%)	ACC (%)	PR (%)	ACC (%)	PR (%)	ACC (%)
40	99.2	98.7	99.42	98.48	99.19	97.74	97.69	95.42	99.68	98.34	97.92	96.81
50	99.08	96.48	97.9	96.19	99.32	97.84	99.09	97.76	99.8	98.28	98.03	96.32
60	99.71	94.88	99.32	95.25	99.34	95.76	99.49	96.11	99.27	95.59	98.06	94.21
70	99.87	93.59	99.62	93.81	99.82	94.35	99.61	94.45	99.57	94.09	98.43	92.86
80	99.85	92.27	99.83	92.6	99.53	92.5	99.28	92.6	99.82	93.17	98.63	91.86
90	99.98	88.58	99.75	91.26	99.9	91.77	99.42	91.77	99.81	91.87	95.66	87.3

note: PR (Precision), ACC (Accuracy)

Table 9 shows the bias values of the calibration data. The average bias value is 2.37 RH%, where the allowed bias tolerance is 3 RH%. Based on the average bias, the bias value has met the allowed tolerance. However, if reviewed further, the band error has not met the expected tolerance, so further adjustment is required.

Table 9. Bias of BME280 humidity sensor at each test point before adjustment.

Measurement point (RH%)	1st calibration bias	2nd calibration bias	3rd calibration bias	4th calibration bias	5th calibration bias	Overall bias of the measurement range
40	0.18	0.34	0.52	0.81	0.49	0.40
50	1.22	0.81	0.70	0.62	0.71	0.81
60	2.73	2.32	2.04	1.92	2.10	2.22
70	4.20	3.89	3.66	3.46	3.68	3.78
80	5.85	5.57	5.45	5.18	5.14	5.15
90	10.02	7.46	7.15	6.74	6.98	7.67

To determine the range of values around a measurement that includes the variability or uncertainty in the data, an error band graph is created. In the context of calibration and measurement, error bands provide information on how far the measurement results can vary from the true or reference value. Figure 5 shows the error band of the BME280 humidity sensor. The error band value is obtained from the largest deviation between the measurement value of the standard measuring instrument and the test measuring instrument. In the temperature sensor calibration, the largest deviation of ± 10.02 was obtained.

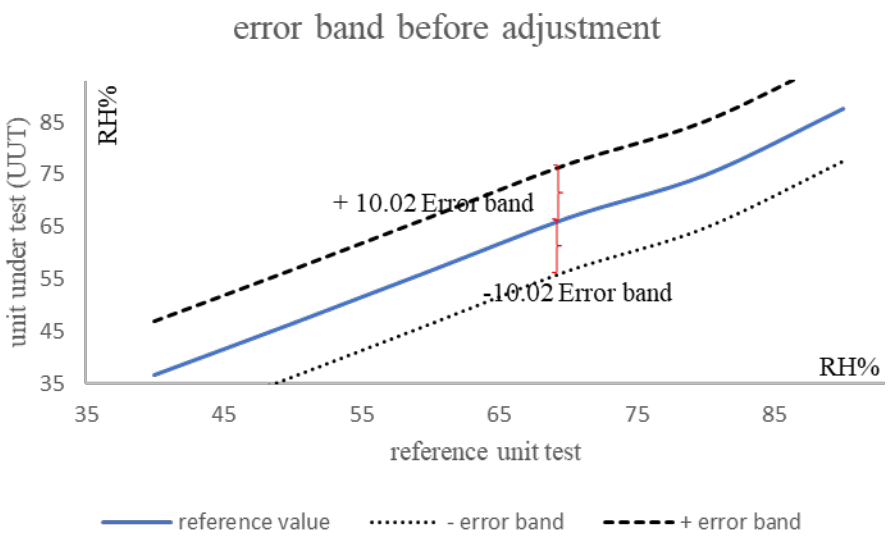


Fig. 5. Error Band on BME 280 humidity sensor before adjustment.

To improve the bias and accuracy values, a graphical analysis of the correlation between the reference unit value and the test unit was performed. Figure 6 shows the linear correlation between the traced gauge and the test gauge for the first calibration data. The same process was carried out to obtain a linear correlation for the second to fifth calibration data, as well as the combination of the five calibration data. The results of these graphs produced a linear function for each calibration data, which is shown in table 10. The coefficient of determination obtained was 1 for each calibration test, indicating that the linear regression model was able to explain all the variation in the data.

Table 10. Linear correlation of reference unit humidity measurement with test unit.

Calibration Data to	Linear function	R^2
1	y = 0.8437x + 4.2496	1.00
2	y = 0.8724x + 3.1505	1.00
3	y = 0.8747x + 3.2346	1.00
4	y = 0.8787x + 3.1848	1.00
5	y = 0.8796x + 2.9909	1.00
1,2,3,4,5	y = 0.8698x + 3.3624	0.99

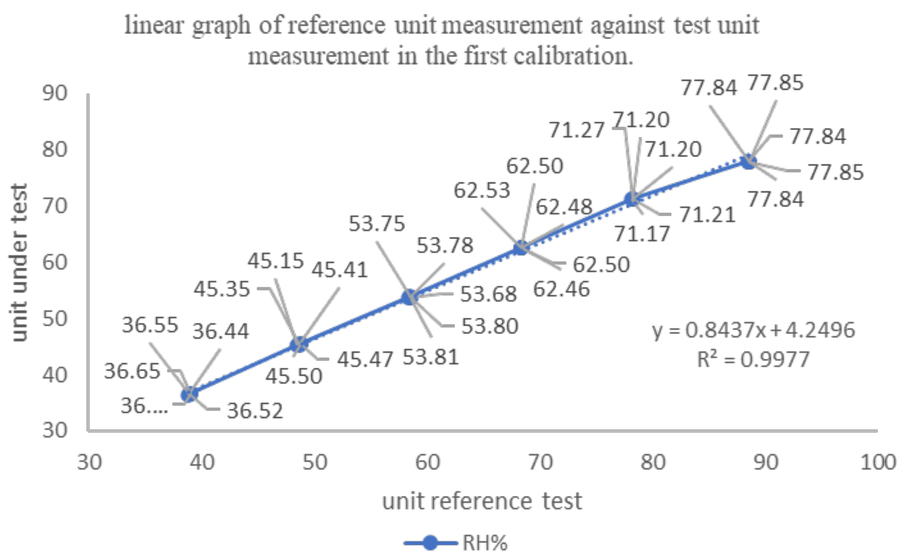


Fig. 6. Linear correlation of humidity measurement between reference unit and test unit.

The precision and accuracy results after tuning are shown in table 11, where the smallest precision value is 97.47%, the largest is 99.98%, with a median value of 99.53%. Meanwhile, the smallest accuracy value was 90.95%, the largest was 98.20%, and the median value was 95.72%.

Table 11. Accuracy and Precision of BME280 humidity sensor at each test point after adjustment.

Measurement Point (RH%)	1st Calibration		2nd calibration		3rd calibration		4th calibration		5th calibration		All five Calibration data	
	PR (%)	ACC (%)	PR (%)	ACC (%)	PR (%)	ACC (%)	PR (%)	ACC (%)	PR (%)	ACC (%)	PR (%)	ACC (%)
40	99.09	94.83	99.37	93.49	99.11	93.22	97.47	90.95	99.65	93.7	98.13	92.39
50	98.99	94.34	97.75	92.85	99.27	94.58	99.02	94.49	99.79	95.11	98.5	93.79
60	99.68	95.8	99.28	95.72	99.3	95.6	99.46	95.92	99.23	95.72	99.3	95.65
70	99.87	96.34	99.6	97.08	99.81	97.3	99.59	97.1	99.55	97.19	98.76	96.05
80	99.84	96.84	99.82	98.2	99.51	98.05	99.24	97.79	99.82	98.12	98.12	96.12
90	99.98	99.26	99.73	98.98	99.9	99.08	99.4	98.49	99.8	99.02	98.3	97.79

note: PR (Precision), ACC (Accuracy)

The bias value after tuning shows improvement in each calibration data. Table 12 shows the bias values obtained. The average bias value after tuning is 1.65, which meets the tolerance allowed by the World Meteorological Organization (WMO). Thus, it can be stated that the tuning is effective for improving the accuracy value. The error band value has improved after adjusting the sensor. The band error obtained after tuning is ±2.24, and the value meets the allowable tolerance.

Table 12. Bias of BME280 Humidity Sensor at each test point after adjustment.

Measurement point (RH%)	1st calibration bias	2nd calibration bias	3rd calibration bias	4th calibration bias	5th calibration bias	Overall bias of the measurement range
40	1.55	2.14	2.13	2.32	2.17	2.06
50	2.14	2.21	2.17	2.08	2.18	2.16
60	2.19	2.00	2.08	1.99	1.98	2.05
70	2.34	1.67	1.67	1.66	1.57	1.78
80	2.31	1.25	1.12	1.11	1.31	1.47
90	0.63	0.66	0.72	0.79	0.68	0.44

BME280 Barometric Pressure Sensor Calibration.

Table 13 shows the accuracy and precision of the BME280 pressure sensor at each test point before adjustment. The smallest precision value is 99.69%, the largest is 99.99%, with a center value of 99.97%. Meanwhile, the smallest accuracy is 99.55%, the largest is 99.95%, with a median value of 99.97%. In addition, precision and accuracy calculations were also carried out directly for five calibration data at each point. As a result, the smallest precision value is 99.58%, the largest is 99.94%, with a median value of 99.87%.

Table 13. Accuracy and Precision of BME280 barometric pressure sensor at each test point before adjustment.

Measurement Point (hPa)	1st Calibration		2nd calibration		3rd calibration		4th calibration		5th calibration		All five Calibration data	
	PR (%)	ACC (%)	PR (%)	ACC (%)	PR (%)	ACC (%)	PR (%)	ACC (%)	PR (%)	ACC (%)	PR (%)	ACC (%)
850	99.92	99.71	99.95	99.74	99.88	99.66	99.88	99.69	99.92	99.71	99.58	99.37
900	99.97	99.76	99.98	99.82	99.69	99.55	99.92	99.71	99.97	99.95	99.72	99.57
950	99.98	99.78	99.99	99.79	99.98	99.78	99.96	99.76	99.98	99.86	99.87	98.62
1000	99.94	99.76	99.97	99.79	99.98	99.8	99.99	99.81	99.98	99.85	99.91	99.74
1050	99.96	99.79	99.99	99.82	99.93	99.76	99.97	99.79	99.97	99.81	99.94	99.77

Despite having the best accuracy value of 99.95%, the correction results still exceed the tolerance allowed by the WMO. Table 14 shows the bias value of the calibration data performed. The average bias value is 1.68, while the allowable tolerance is 0.15. Therefore, additional tuning is required to correct the bias value to match the expected tolerance.

Table 14. Bias of BME280 barometric pressure sensor at each test point before adjustment.

Measurement point (hPa)	1st calibration bias	2nd calibration bias	3rd calibration bias	4th calibration bias	5th calibration bias	Overall bias of the measurement range
850	1.83	1.80	1.86	1.65	1.80	1.79
900	1.84	1.46	1.30	1.88	0.21	1.34
950	1.88	1.85	1.85	1.89	1.16	1.62
1000	1.77	1.81	1.87	1.87	1.33	1.73
1050	1.82	1.80	1.84	1.86	1.67	1.80

To determine the range of values around a measurement that includes the variability or uncertainty in the data, an error band graph is created. In the context of calibration and measurement, the error band provides information on how far the measurement result can vary from the true or reference value. Figure 7 shows the error band of the BME280 pressure sensor. The error band value is obtained from the largest deviation between the measurement of the standard measuring instrument and the test measuring instrument. In the temperature sensor calibration, the largest deviation found was ±1.89.

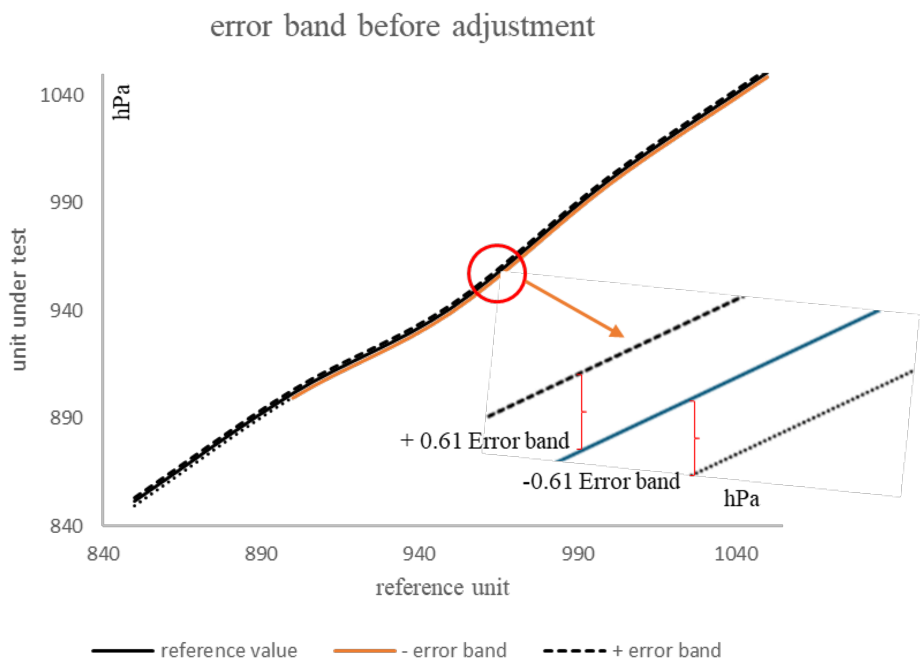


Fig. 7. Error Band on BME 280 barometric pressure sensor before adjustment.

To correct the bias value, a graphical analysis of the correlation between the reference unit and test unit values was performed. Figure 8 shows the linear correlation between reference units and test units for the first calibration data. The same process was carried out to obtain a linear correlation for the second to fifth calibration data, as well as the combination of all five calibration data. The results of these graphs produced a linear function for each calibration data, which is shown in table 15. The coefficient of determination obtained is 0.99 for the fifth calibration, while in the other calibrations it reaches 1, indicating that the linear regression model obtained is able to explain all the variations in the data.

Table 15. Linear correlation of reference unit barometric pressure measurement with test unit.

Calibration Data to	Linear function	R^2
1	y = 0.9998x + 1.9912	1
2	y = 1.0006x + 1.1275	1
3	y = 1.0011x + 0.72	1
4	y = 1.0008x + 1.0642	1
5	y = 1.0017x - 0.3391	0.99
1,2,3,4,5	y = 1.0008x + 0.9088	1

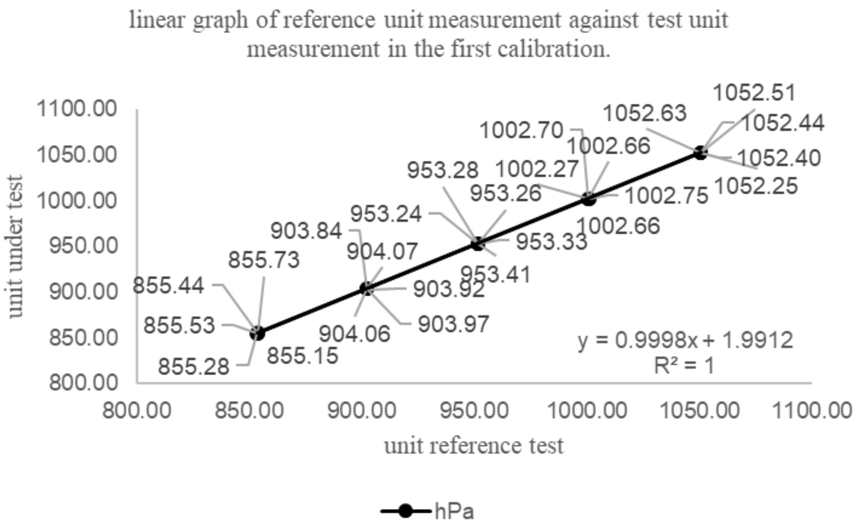


Fig. 8. Linear correlation of barometric pressure measurement between reference unit and test unit.

The precision and accuracy results after tuning are shown in table 16, where the precision values before and after adjusting did not change. However, the accuracy value has changed, with the lowest accuracy of 99.65%, the highest of 99.99%, and the median value of 99.95%.

Table 16. Accuracy and Precision of BME280 barometric pressure sensor at each test point after adjustment.

Measurement Point (hPa)	1st Calibration		2nd calibration		3rd calibration		4th calibration		5th calibration		All five Calibration data	
	PR (%)	ACC (%)	PR (%)	ACC (%)	PR (%)	ACC (%)	PR (%)	ACC (%)	PR (%)	ACC (%)	PR (%)	ACC (%)
850	99.92	99.92	99.95	99.93	99.88	99.86	99.88	99.87	99.92	99.92	99.59	99.59
900	99.97	99.96	99.98	99.96	99.69	99.65	99.92	99.91	99.97	99.95	99.69	99.69
950	99.98	99.97	99.99	99.97	99.98	99.97	99.96	99.95	99.98	99.9	99.88	98.82
1000	99.94	99.94	99.97	99.96	99.98	99.98	99.99	99.99	99.98	99.91	99.91	99.9
1050	99.96	99.96	99.99	99.99	99.93	99.93	99.97	99.97	99.97	99.93	99.92	99.91

note: PR (Precision), ACC (Accuracy)

The bias values after tuning showed improvement for each calibration data. Table 17 displays the bias values obtained, with an average bias of 0.06 after tuning. This value meets the bias tolerance allowed by the WMO. Thus, it can be stated that the tuning successfully improved the accuracy of the sensor. In addition, the band error value also improved after adjusting, with the obtained band error of ±0.8.

Table 17. Bias of BME280 barometric pressure sensor at each test point after adjustment.

Measurement point (hPa)	1st calibration bias	2nd calibration bias	3rd calibration bias	4th calibration bias	5th calibration bias	Overall bias of the measurement range
850	0.01	0.17	0.20	0.10	0.02	0.06
900	0.03	0.21	0.41	0.10	0.21	0.06
950	0.08	0.15	0.08	0.06	0.80	0.18
1000	0.02	0.08	0.04	0.00	0.71	0.12
1050	0.04	0.04	0.04	0.05	0.45	0.09

Conclusion

Many sensors are available for low-cost weather station construction, but their use must be considered before they are implemented in the system. It is important to make adjustments to the sensor so that the precision and accuracy values increase, resulting in a bias that complies with the standards allowed by the WMO. In this study, adjustment and calibration of the sensor were carried out. After adjustment, the calibration results on the BME280 sensor show a temperature sensor accuracy of 99.74%, humidity sensor accuracy of 99.26%, and pressure sensor accuracy of 99.99%. This improvement increases the bias value, thus meeting the tolerance allowed by WMO. The next phase of this research involves the development of a wireless sensor system for blind calibration.

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