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Developing the altitude and communication subsystem using COTS components applied to the Tycho CubeSat

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Abstract. *The "Tycho" CubeSat is a type of small satellite developed to be a scientific platform for students and enthusiasts that need to perform atmospheric experiments at a low cost without losing considerable features. In this paper is studied and developed the electronic telecommunications and navigation subsystem using the LoRa - Long Range and Low power technology and the BMP280 to take measurements of altitude, temperature and pressure, both Commercial Off The Shelf (COTS) components. This work is a subsystem of a small satellite that was developed to be on board of a balloon launch system. The first part of this project aims to prototype a viable solution and then compare with current techniques implemented in the components to best fulfill the requirements of this platform. As part of calibration measurement of BMP280 and certifying the wireless communication data send by LoRa is used a Parrot BeBop drone.*

Keywords: LoRa; CubeSat; BMP280; Altitude; COTS.

1. Introduction

The CubeSat concept was first created in 1999 by Jordi Puig-Suari and Bob Twiggs as a way to enable graduate students to design, build, test and operate in space a spacecraft with capabilities similar to that of the first spacecraft, Sputnik (Helvajian and Janson 2008).

The satellite development has a expensive cost, for example, the CBERS-China Brazil Earth Resources Satellite 04A, launched in the last year at the Taiyuan base at China, had a budget of the order of US$ 35 million and a development time of about two years (INPE 2019). The CubeSat technology employ the same idea of the bigger satellites, but using commercial components to allow Universities and Students to apply the concepts studied in the class (Stefański and Król 2019).

With that in mind, the final goal is to develop a low-cost CubeSat platform using Commercial Off The Shelf components for students to be able to perform experiments at the high atmosphere environment. In small satellites, the altitude measurement is quintessential. It is used to determinate the accurate orbit and, in CanSats, is also used to open the parachute at the right time to recover the system safely. One of the satellite subsystems is the TT&C (Telemetry Tracking and Command), in this work we developed a new system using a LoRa technology to perform a communication between the CubeSat and the base station. LoRa means Long Range which propose a radio system with low power consumption. It is based on spread spectrum modulation techniques and was developed by Semtech (Restivo 2019).

The main objective of this project is to calibrate, characterize and evaluate the BMP280 pressure and temperature sensor. It will be explored different approaches to altitude calculation based on the pressure and temperature gathered by the sensor.

The results will be later utilized in the implementation of the Tycho CubeSat navigation subsystem that, when finished, is intended to be embedded on a High Altitude Balloon.

2. Methodology

One of the main aspects of the project is the hardware, so its first step is to define the components to be used, according to the necessities. In order to keep the electronic circuit clean and easy to manage we used a simple temperature and pressure sensor paired with a ESP32 based microcontroller transmitting data using the LoRa technology.

In this work was used the pressure and temperature sensor BMP280 manufactured by Bosch Sensortec. The datasheet specification gives temperature range from -40°C up to +85°C and precision on the order of ±0.12 hPa (relative) or ±1 hPa (absolute). The sensor uses the I^2C digital interface, which can be easily integrated with the microcontroller (Bosch Sensortec 2018).

The Heltec WiFi LoRa 32 V2 is used as the microcontroller and is based on the ESP32 series (Heltec Automation 2019). The data is sent and displayed using the OLED technology embedded on LoRa technology (Springer et al. 2000). In Figure 1 is shown the electrical connections between the sensor and the microcontroller, the GPIO terminals 21 and 22 from the ESP32 are connected to SCL and SDA respectively. This electrical connection was created using Fritzing, a free open-source hardware designing tool.

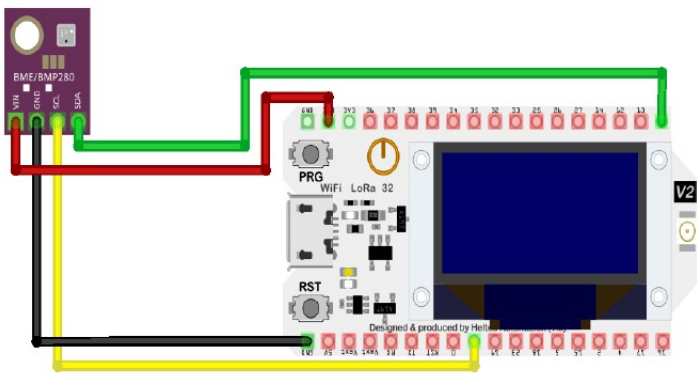

Figure 1. Electronic connection between the ESP32 and the BMP280 sensor.

The next step is to decide the most suitable methods to calculate the approximate altitude. In this work we decided on three different approaches to calculating the altitude using the pressure and temperature of the environment.

The Equation 1, provided by the National Oceanic and Atmospheric Administration (National Oceanic and Atmospheric Administration 2020), takes the current (P) and base level (P_b) pressure in hPa to determine the altitude. The result is given in feet and to convert it to meters we multiply by 0.3048.

$$h_{ft} = \left(1 - \left(\frac{P}{P_b}\right)^{0.190284}\right) \cdot 145366.45 \qquad (1)$$

The Equation 2 is the inverse function of the barometric formula, solved for h, without Lapse Rate, observed by Edmund Halley (Halley 1686) and created by Pierre-Simon Laplace (Laplace 1825). This formula considers the sea level temperature to be 15°C and the result is the estimated altitude in meters.

$$h_m = \frac{25000}{3} \cdot \ln\left(\frac{P_b}{P}\right) \tag{2}$$

To achieve a better precision, we can use the Lapse Rate of the current atmosphere layer while using the barometric equation, for each layer of the atmosphere (defined by b), we use different equations and constants:

$$P(P_b,\ T_b,\ L_b,\ h,\ h_b) = \begin{cases} L_b \neq 0, & P = P_b \cdot \left[\frac{T_b}{T_b + L_b \cdot (h - h_b)}\right]^{\frac{g_0 \cdot M}{R \cdot L_b}} \\ L_b = 0, & P = P_b \cdot \exp\left[\frac{-g_0 \cdot M \cdot (h - h_b)}{R \cdot T_b}\right] \end{cases} \tag{3}$$

In this formula, P_b is the pressure at the bottom of the layer (static pressure), T_b is the temperature at the bottom of the layer (standard temperature), L_b is the standard temperature lapse rate, h is the altitude above sea level, h_b is the altitude at the bottom of the layer, R is the universal gas constant, g_0 is the gravitational acceleration and M is the molar mass of Earth's air, all in SI units.

Table 1. Parameters for each atmospheric layer used on the barometric formula (National Oceanic and Atmospheric Administration et al. 1976).

Layer b	**Height above sea level [m]**	**Static Pressure [Pa]**	**Standard Temperature [K]**	**Lapse Rate [K/m]**
0	0	101325.00	288.15	-0.0065
1	11000	22632.10	216.65	0.0
2	20000	5474.89	216.65	0.001
3	32000	868.02	228.65	0.0028
4	47000	110.91	270.65	0.0
5	51000	66.94	270.65	-0.0028
6	71000	3.96	214.65	-0.002

Solving this equation for h in low altitudes (up to 11 Km), we can achieve Equation 4.

$$h_m = h_b + \frac{T_b}{L_b} \cdot \left[\left(\frac{P}{P_b}\right)^{\frac{-R \cdot L_b}{g_0 \cdot M}} - 1\right] \tag{4}$$

All the equations were implemented using the Arduino IDE, the code used to develop and perform the communication test between the base station and the subsystem satellite is available at the project's GitHub page (Vaz 2019).

The PCB electronic circuit using the ESP32 and the BMP280 sensor was attached to the top of a drone, model Parrot BEBOP 2, as shown in Figure 2 and used the drone battery as source to the entire electronic system. We performed four trials using eight different altitudes and two different scales of altitude, relative (in comparison to the ground level) and absolute (in comparison to the sea level): 1m, 5m, 10m, 15m, 20m, 30m, 40m and 50m. The 1st and the 3rd tests started at the ground and progressed until the 50m mark, the 2nd and the 4th had the inverse order, starting at 50m and descending to the ground. The measured results were averaged to account for any reading anomalies.

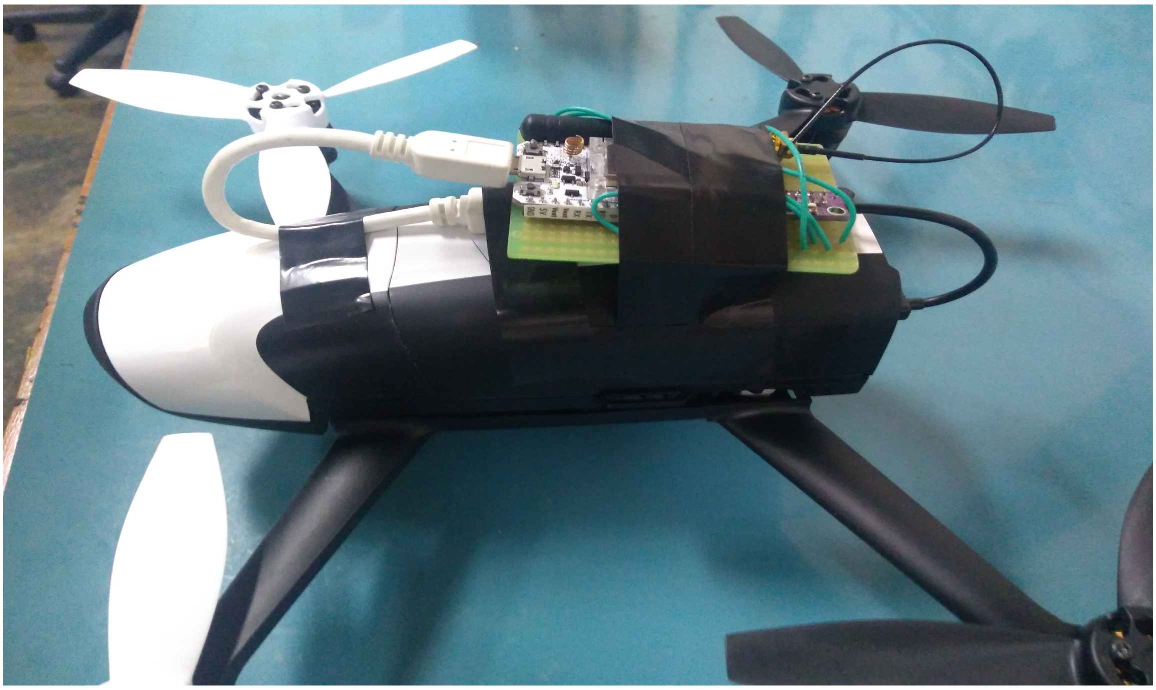

Figure 2. PCB using the ESP32 and the BMP280 sensor attached to the drone.

3. Results and Discussion

The results of the relative altitude test, comparing the measured and the expected data, is shown in Figure 3. As we can see, the green, blue and cyan represent Equations 1, 2 and 3 respectively.

The entire test was performed at an altitude (ground level) of 618m above the sea level and approximately 28° Celsius.

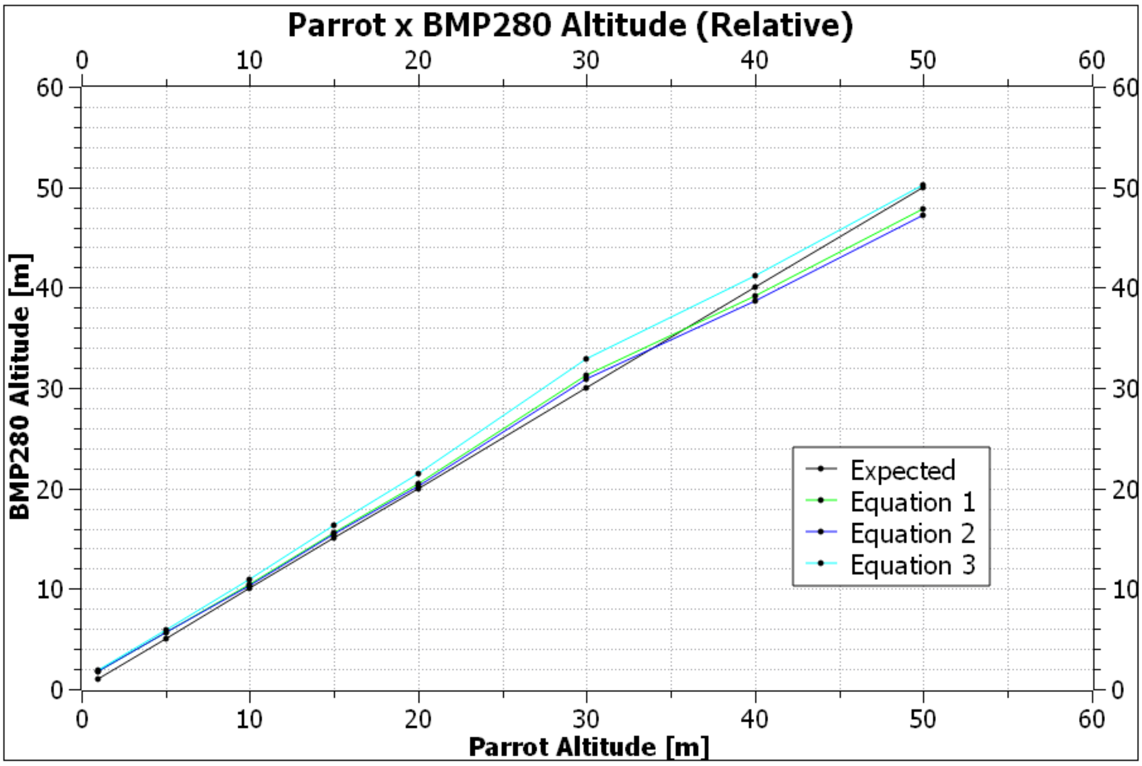

Figure 3. Relative altitude average results curve.

The Figure 4 shows the results when using the absolute altitude in relation to the sea level.

The analysis of data was realized using the sum of squared estimate of errors (SSE), Equation 5, as a way to increase the deviation of greater errors and find the best overall fitting formula. To calculate the SSE we take the difference of the observed (M_i) and expected data (E_i) for each measurement (i), square it and then sum all the obtained values. Lower values for the SSE mean the data obtained is more precise to the system.

$$\sum_{i=0}^{n}(M_i - E_i)^2 \tag{5}$$

An implementation example of the SSE equation is shown in Table 2.

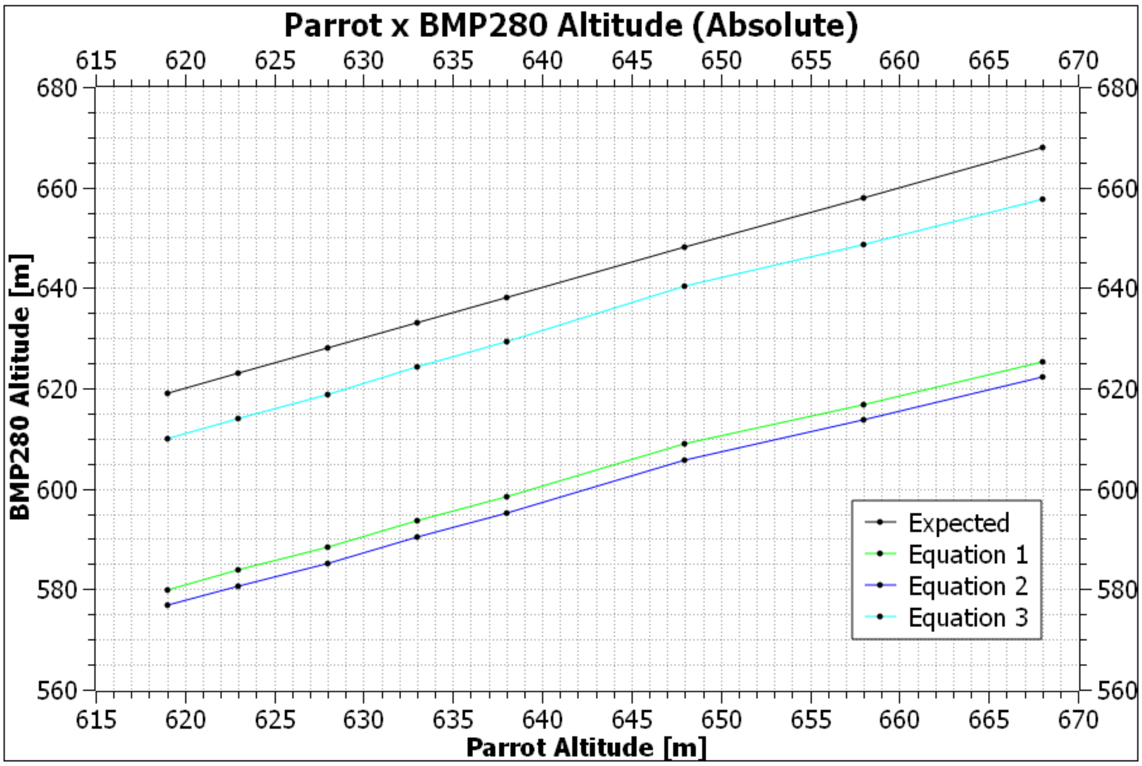

Figure 4. Absolute altitude average results curve.

Table 2. SSE calculation example

Expected	Observed
1	1.80
5	5.67
10	10.41
15	15.58
20	20.41
30	31.23
40	39.15
50	47.80
SSE	8.86569375

The SSE calculation was performed to all equations, considering the relative and absolute data. The results are shown in Table 3.

Table 3. SSE result for each method.

Method	SSE	
	Relative	Absolute
Eq1	8.86569375	12816.55159
Eq2	11.2559	14926.59753
Eq3	16.1359125	654.7787375

As it is shown on Table 3, the best fitting for relative and low altitudes is Eq1. The ratio (D_r) between the worst (Eq3) and best errors is about 1.82.

When increasing the altitude or using absolute altitude, Eq3 is the best performer. The ratio (D_a) between the worst (Eq2) and the best performer is approximately 22.8. Compared to Eq1, the ratio is 19.59, a tenfold increase in the relative error produced by the equation.

Analysing the results gathered we have two formulas that stand out, Equation 1 and Equation 4. Equation 1 works best when using low magnitudes of altitude, having a great precision. Equation 4 is best used when in greater altitudes, deviating less from the real altitude compared to the other equations.

Using the raw data collected, it can be observed that Equation 4 is also more stable against pressure variations. For example, between the second and third test at 668m, the variation for Equation 4 is 0.18%, while the other formulas have an average variation of 1.46%.

Another advantage of the last solution is that it can be adjusted to any atmospheric layer. This will be of great influence when applying it to the Tycho CubeSat as it is predicted to reach up to 40km.

4. Conclusion

In this work was developed a small satellite subsystem using commercial off the shelf components, the BMP280 as temperature, pressure and altitude sensor and a ESP32 microcontroller embedded with LoRA Radio to work as a communications subsystem.

The altitude is one of the relevant parameters to be monitored on the satellite, we used three ways to calculate this parameters using pressure and temperature which was measured by the BMP280 sensor. The final results show a good fit when using the Equation 4 to calculate the altitude. It is the best analyzed subject to be implemented into the Tycho CubeSat, as it has a great precision in high altitudes and can be easily adjusted to all atmospheric layers.

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