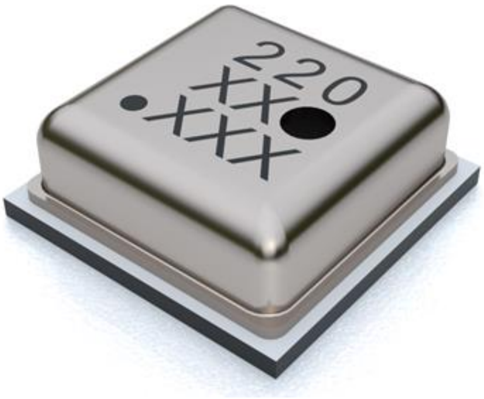

Height measurement with the ENS220

Application note

Application note – height measurement with the ENS220

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1 Introduction

Atmospheric pressure results from the force of gravity acting on the mass of the air column extending from the point of measurement to outer space. Consequently, barometric pressure varies with changes in the altitude of the measurement point. While the pressure difference caused by small variations in altitude is typically small, the ENS220 pressure sensor can measure these differences with high accuracy and at a high sample rate, all while maintaining low power consumption. These capabilities enable precise height measurements using a barometric pressure sensor, achieving accuracies potentially better than a few centimeters, depending on the sample rate and environmental stability.

Many applications benefit from height measurement. Some examples are:

- Indoor localization,
- Localization of goods in a warehouse,
- Robotic and industrial applications in combination with inertial measurement sensors,
- Wearable devices for detecting vertical displacement or other physical activities,
- Altitude control for drones.

However, height is not the only factor influencing barometric pressure. Atmospheric dynamics, such as temperature changes or weather events including cloud movements, can cause significant pressure fluctuations over time. Moreover, any activity that alters the density or speed of the air, such as opening or closing a door or window, can impact barometric readings.

In this application note, we first describe the methods for calculating height based on pressure. We then explore various configurations in which the pressure sensor can be utilized for measuring absolute height or changes in height. Factors that may disrupt measurements for each configuration are discussed and strategies to mitigate effects are presented.

Test results using the ENS220 barometric pressure sensor are provided, highlighting the sensor's performance and its potential of enabling advanced applications.

2 Pressure to height conversion

There are multiple formulas to convert pressure to height for different kinds of approximations. Equation (1) is a well-known formula that considers the pressure change with altitude and temperate [1]

$$z = -\frac{RT}{g}\ln\frac{P}{P_0}\ , \tag{1}$$

where

- z is the elevation in meters,
- *R = 287.053 J/(kg K)* is the specific gas constant
- *T* is the absolute temperature in kelvins,
- *g= 9.80665 m/s*^{2} is the acceleration due to gravity at sea level,
- *P* is the pressure at a given point at elevation *z* in Pascals, and
- P_0 is pressure at the reference point, P_0= *101,325 Pa* at sea level.

Based on equation (1) the following formula can be used to calculate the height difference between two points with pressures P_2 and P_1.

$$h = z_2 - z_1 = \frac{RT}{g}\ln\frac{P_1}{P_2} \tag{2}$$

For high altitudes (higher than 4 km) it can be beneficial to take the change of temperature with altitude into account. Assuming a linear decrease in temperature with altitude (L) then the height can be calculated from temperature as [2]:

$$z = \frac{T_0}{L}\left(\left(\frac{P}{P_0}\right)^{\frac{-LR}{g}} - 1\right), \tag{3}$$

By setting $L = -6.5 \times 10^{-3}$, $T_0 = 288.15\mathrm{K}$ we arrive at the following formula.

$$z = 44331 - 4946.54\ P^{0.1902632} \tag{4}$$

The difference for low altitudes however is small. Height calculation using pressure is plotted in *Figure 1* using equations (1) and (4).

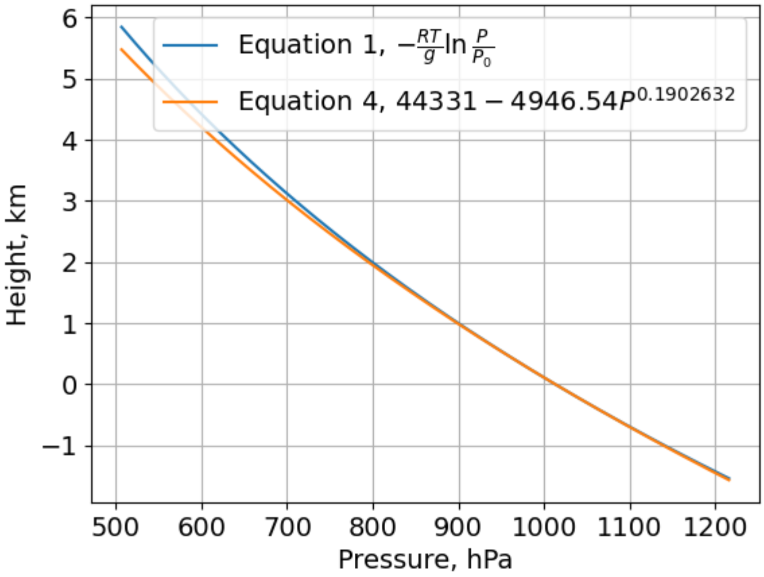

Figure 1. Calculation of height from sea level using barometric pressure

For many applications we are interested in small changes in height. Then equation (1) can be linearized as follows:

$$\Delta z = \frac{RT}{g}\frac{\Delta P}{P}\ . \tag{5}$$

We obtain:

$$\Delta z\ [\mathrm{m}] = 0.0846[\mathrm{m/Pa}]\ \ \Delta P = \frac{\Delta P\ [\mathrm{Pa}]}{11.8\ [\mathrm{Pa/m}]} \tag{6}$$

Assuming normal condition T =20 C = 293.15K and P=101325 Pa.

3 Height Measurement configurations

Figure 2 shows several configurations of pressure sensors for measuring height.

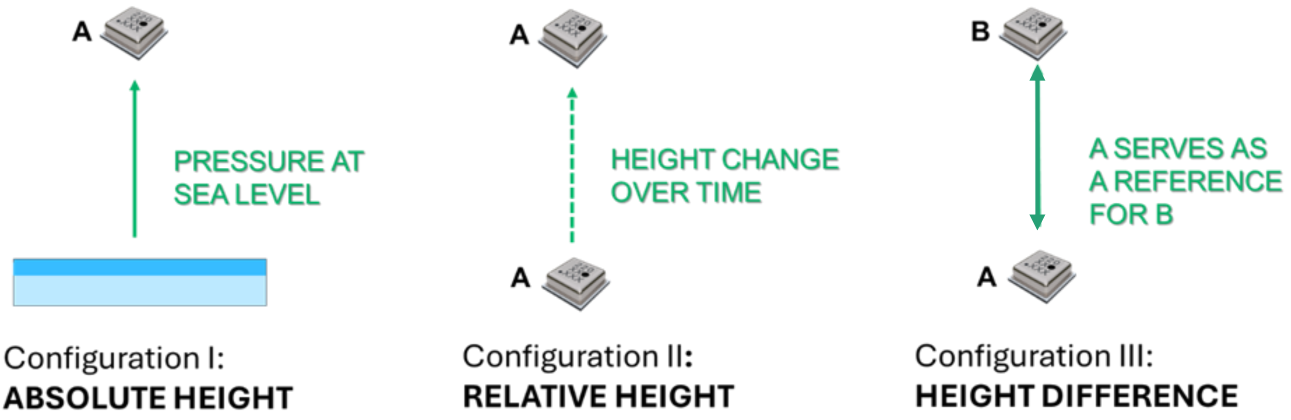

Figure 2. Example configurations of ENS220 pressure sensors for measuring height

First Configuration: Single Sensor height measurement

In this configuration, a single ENS220 pressure sensor determines the height from sea level by measuring the current atmospheric pressure at time t and location X. The reference pressure P0, however, might be recorded at a different location Y and a different time t-Δt.

$$\text{Height: } h = -\frac{RT}{g}\ln\frac{P(t,X)}{P_0(t-\Delta t,Y)} \tag{7}$$

It is important to note that the expected error increases with the time difference (Δt) and the distance between the measurement and reference locations. Standard reference pressure P_0=101325 Pascal can be used, though this introduces significant errors, potentially on the order of hundreds of meters. A more accurate approach is obtaining reference pressure P_0 from a nearby weather station, which can reduce errors to less than 10 meters, a satisfactory level for many applications. This configuration's accuracy is predominantly affected by atmospheric pressure changes over time.

Second Configuration: Single sensor height change measurement

This configuration uses one ENS220 pressure sensor and measures the vertical displacement of the sensor over time using the following formula:

$$\text{Height change: } \Delta h(t) = -\frac{RT}{g}\ln\frac{P(t)}{P(t-\Delta t)} \tag{8}$$

The limiting factor here is the stability of the atmospheric pressure during the measurement period. As subsequent sections will discuss, the longer the time span, the more significant the effect of natural atmospheric pressure changes would be.

Third Configuration: Dual-Sensor Method

This configuration uses two ENS220 sensors to measure the height difference between two points, effectively minimizing external interferences:

$$\text{Height difference: } \Delta h = -\frac{RT}{g} \ln \frac{P_1(t)}{P_2(t)} \tag{9}$$

By using two sensors, this approach cancels out most of the atmospheric variations that can affect a single sensor, providing a more reliable and accurate measurement of height differences.

4 Interfering factors for height measurement

For configuration 1 and 2 of Figure 2 changes in atmospheric pressure dominate the obtainable accuracy. Atmospheric pressure can vary over a large area due to environmental changes. Additionally, local variations, such as those caused by opening and closing doors and windows in indoor settings, can also affect pressure readings. As discussed in later sections, these changes in air pressure typically introduce errors that are considerably larger than the inherent accuracy of the ENS220 sensor.

For configuration 3 of Figure 2 the influence of atmospheric pressure changes is largely cancelled. This configuration effectively cancels out local atmospheric disturbances, provided that both sensors are situated within the same environment. In this configuration the primary accuracy limitation over short periods is the noise level of the ENS220 sensor. Over longer periods, the main factors are the stability and drift of the sensor.

4.1 Atmospheric pressure change over a long period of time

Barometric air pressure is always changing, caused by changes in air density. Air density is related to temperature and humidity. Figure 3 shows the sea level pressure (SLP) converted to height change. The height derived from the barometric pressure can change up to ±200 meters over time. If the SLP is known from a recent measurement the height estimate can be improved. The error is random and depends on time difference Δt between the reference and measured pressure as described in equation (10).

$$\text{Heigh error}(t, \Delta t) = \text{Estimate of height} - \text{actual height} = \frac{RT}{g} ln \frac{P(t)}{P_0(t-\Delta t)} - \frac{RT}{g} ln \frac{P(t)}{P_0(t)} = \frac{RT}{g} ln \frac{P_0(\Delta t)}{P_0(t-\Delta t)} \qquad (10)$$

To gain insight into typical changes over time we have plotted the Root Mean Square (RMS) error made when using a pressure reference from the past for multiple locations in Figure 4. On the left the data from weather stations in the United States and on the right the data from weather stations in the Netherlands is plotted. The RMS error made by using a pressure reference from one hour ago for all these locations is around 6 meters. The expected error increases as the time from updating reference increases. Depending on the location the expected error saturates after 2 days and reaches around forty to hundred meters.

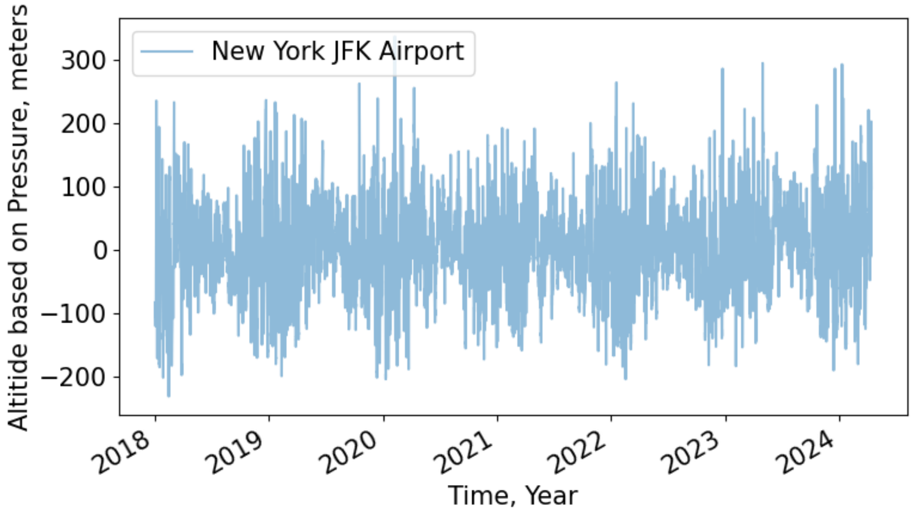

Figure 3 Sea level pressure (SLP) converted to height in meter for New York JFK airport, Source: https://www.ncei.noaa.gov/access/search/data-search/global-hourly

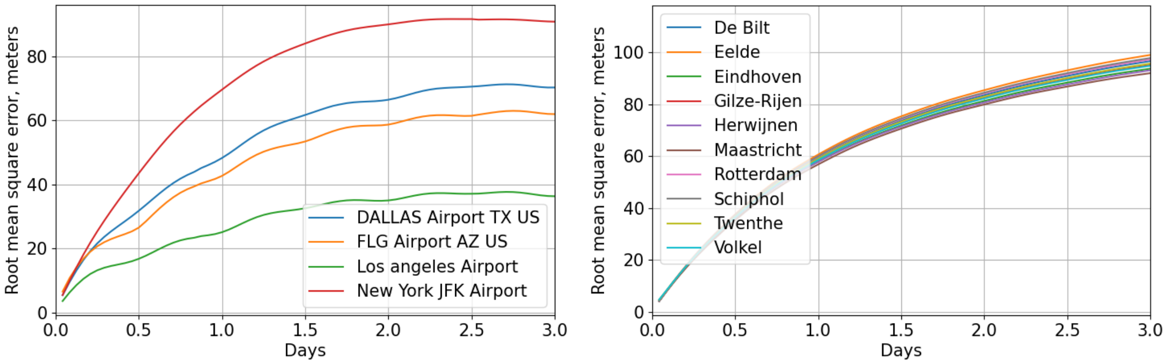

Figure 4 Error caused by using a lagging value for reference pressure. X axis shows the time from updating reference pressure and Y-axis shows the Root Mean Square (RMS) error. The left figure is from several airport weather stations in the United States and the right figure is from weather stations in the Netherlands.

4.2 Effect of distance from reference pressure

In Configuration 1 (see Figure 2), obtaining a reference pressure as close as possible to the measurement site is ideal. However, the nearest weather station can sometimes be kilometers away. To determine the effect of this distance on height measurement accuracy, pressure data from weather stations in the Netherlands was analyzed over several decades. The analysis showed that the mean square error in height measurements increases linearly with distance from reference point, at a rate of 1 meter RMS error for every 10 kilometers distance. This demonstrates that by using data from nearby weather stations we can achieve an altitude accuracy of a few meters.

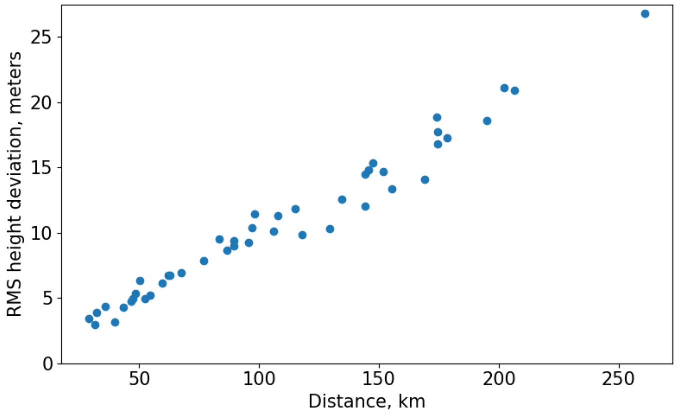

Figure 5 Error caused by using a reference pressure at a difference location than the measurement point. X axis shows the distance between reference and measurement point and Y-axis shows RMS error. The data is from weather stations in the Netherlands.

4.3 Atmospheric pressure change over a short period of time

The fluctuation of pressure over brief intervals is important for applications that require measurements of height changes or vertical speed, as depicted in Configuration 2 of Figure 2. Figure 6 shows the standard deviation (STD) and the 90% interval of expected error caused by using an outdated value for reference. For instance, in a scenario involving the free fall of an object from a height of 1 meter, which takes approximately 0.5 seconds, the change in pressure during this half-second can serve as an indicator for detecting the fall. During this 0.5 second however the atmospheric pressure changes and create an error in the height derived from the pressure. From Figure 6 the STD of error within 0.5 seconds is around 4 cm and 90% of times the error is within an interval of 7 cm (if h is the estimated height then 90% of times the actual height is within [h-7cm, h+7cm]).

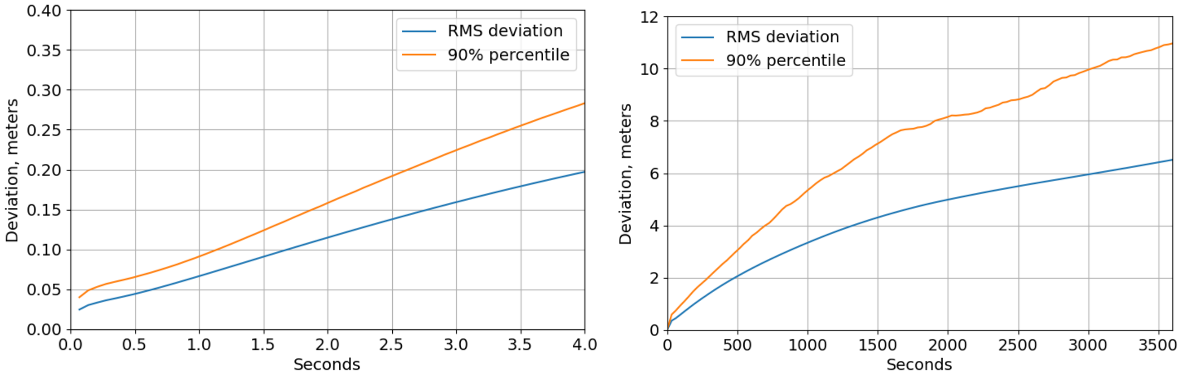

Figure 6 Standard deviation and 90% interval for error caused by using a lagged value for reference pressure. X axis shows the time from updating reference pressure and Y-axis shows the error.

4.4 Atmospheric pressure change caused by local events

Local events that compress or decompress air, such as the opening and closing of doors and windows, can significantly change air pressure. When a door or window opens inward, the air within the room is temporarily compressed, resulting in a measurable increase in pressure. This change typically occurs within approximately 0.5 seconds and can be accurately detected by the ENS220 pressure sensor. The magnitude of the pressure fluctuation—and consequently the corresponding apparent height change—depends on several factors: the size of the room, the dimensions and velocity of the door or window, and how well the room is sealed from external environments.

Figure 7 shows pressure readings from two sensors located in the same room during multiple events of doors and windows opening and closing. The slow trend of barometric pressure changes due to external atmospheric conditions is removed here. The height calculated from barometric pressure can vary by up to a meter during such indoor events. Both sensors register each event. The difference between the signals from the two sensors is also plotted, illustrating:

- the local events are measured with the same amplitude by both sensors,
- the sensor noise is considerably smaller than the effects of these local events.

Figure 8 shows a close-up view of a door opening and closing event. The left side of the figure shows the signals from two sensor in the same room, while the right side displays the signals from sensors located on different floors. The data show that when sensors are in the same room, the impact of indoor events is entirely cancelled in the difference signal. However, when sensors are placed far apart, as seen on the right, the indoor events are recorded at different times and with varying amplitudes, resulting in the presence of these events in the difference signal.

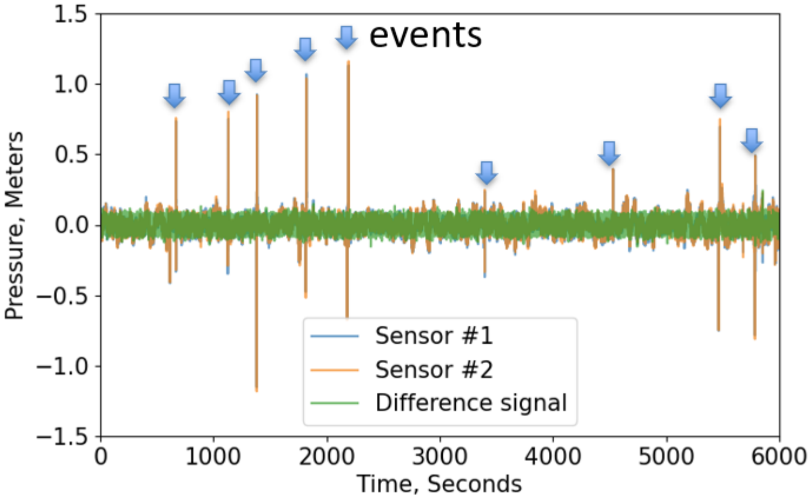

Figure 7. Door and windows events in a residential building and pressure signals from two ENS220 pressure sensors in the same room. Sensor settings are OVP=32 and CONVTIME=2ms which results in a sample rate of approximately 15.6 sample/ seconds.

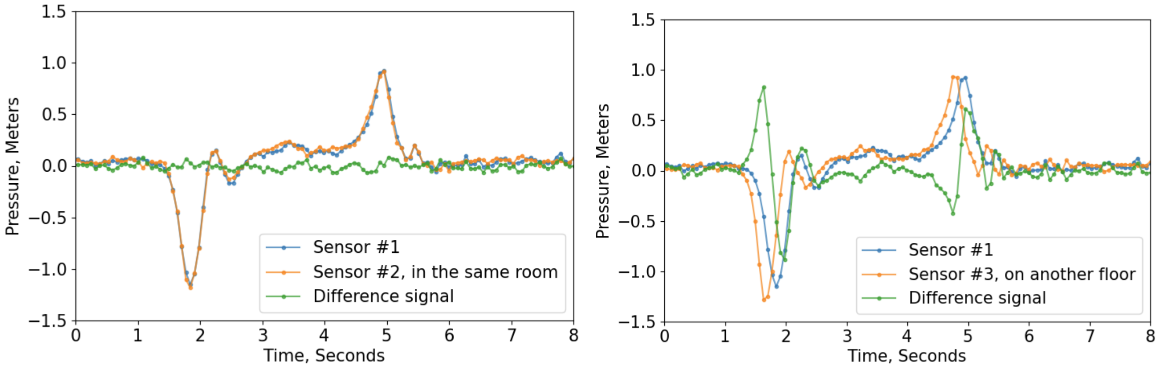

Figure 8 Comparing the pressure signals from different locations in response to indoor events

4.4.1 Mitigating error caused by local events

Height measurement error caused by local events needs to be mitigated when an accuracy of better than 1 meter is required. Depending on the sensors configuration different method can be used.

1- **Cancelation by using the difference signal:** When two sensors are placed close together, indoor events are cancelled from the difference signal as shown in Figure 8. This configuration allows for reliable measurement of the height difference between the sensors without significant interference from indoor events.

2- **Single Sensor or Distant Sensors:** If only one sensor is used (Figure 2 configuration 2), or if two sensors are positioned far apart (such as one sensor on the ground floor and another on a different floor), indoor events can be mitigated using the following methods:
   a. **Low pass filtering**: Since indoor events typically last around 0.5 seconds, a low pass filter with a bandwidth between 0.1 and 0.3 Hz can effectively eliminate these disturbances.
   b. **Selective Data Omission:** Indoor events, lasting about 0.5 seconds, can cause pressure changes equivalent to around one meter in height, but the pressure typically returns to its baseline afterward. To filter out these events, sensor readings can be buffered for 0.5 seconds. Readings that meet these specific conditions are then omitted.

4.5 Sensor offset

The ENS220 pressure sensor delivers state-of-the-art absolute accuracy of ±50 Pa, translating to an absolute height accuracy of approximately ±4 meters. In Configuration 1, as shown in Figure 2, this degree of accuracy is likely to be overshadowed by greater uncertainties due to time lag and the difference in location of the reference point. In Configuration 2, where only one sensor is used and the focus is on the change in height, the initial offset is cancelled. Thus, the relative accuracy of 2.5 Pa becomes crucial, achieving a height accuracy of ±20 cm for a height step of 84 m (1 kPa). The ENS220 offers a resolution of 1/64 Pa, allowing for further enhancement of relative accuracy through individual sensor calibration.

For Configuration 3, which uses two sensors to determine the height difference, achieving accuracies on the order of 20 cm requires either post-production calibration or automatic in-field calibration.

To minimize the impact of external factors such as mechanical deformation, heat from electronics, and electronic noise on the sensor, it is essential to follow the design guidelines for the ENS220 as outlined in [3].

5 Advantages and limitations

For applications like altitude control for drones, technologies designed to measure distance, such as ultrasound, optical time of flight (ToF), radar, and camera imagery [4], can be adapted for height measurement. However, the ENS220 barometric pressure sensor offers unique benefits and complementary features that make it particularly advantageous for height measurement. Here ENS220 can be used as a stand-alone solution or combined with other techniques as it provides unique benefits and complementary features.

Advantages of using the ENS220 pressure sensor for height measurement:

- **Low Power Consumption**: The ENS220 operates on just a few microwatts of power, significantly lower than ultrasound, camera, and radar modules, which typically require around 100 milliwatts.
- **Obstacle Robustness**: Unlike other technologies, height measurement with the ENS220 is not hindered by obstacles in the sensing path since it does not require a direct line of sight to the ground. Additionally, it is unaffected by conditions such as fog, smoke, or rain that can impact optical sensors.
- **360-Degree Field of View**: The barometric pressure sensor does not require a direct sensing path and can function within a box, needing only a small air gap to accurately measure height.
- **Compact Size**: The ENS220 has a minimal footprint, occupying only 2 mm × 2 mm of space without the need for additional components like light sources, antennas, or ultrasound transducers.
- **Wide Operational Range**: ENS220 can measure heights ranging from a few centimeters to several kilometers, far exceeding the capabilities of optical and ultrasound sensors, which are generally limited to tens of meters.
- **Passive Operation**: Since the ENS220 does not emit any signals, it is immune to interference from other devices operating in the vicinity.
- **Tilt Independence**: The sensor accurately measures height regardless of its angle of inclination, unlike other technologies where a tilt can result in incorrect height measurements.

Limitations of using the ENS220 pressure sensor for height measurement:

- **Accuracy**: The precision of the ENS220 is limited to a few centimeters, which may be insufficient for some applications.
- **Environmental Influence**: Performance can be affected by environmental changes that alter barometric pressure like opening and closing door. Also, events that increase the barometric pressure variation like storms and strong winds can have an impact.
- **Media Dependency**: Its functionality is restricted to air; For example, it cannot work in vacuum.
- **Indirect Ground Detection**: The sensor measures height from the start of the atmosphere downward and does not directly detect the ground surface, which could be a limitation in certain applications.

In addition to traditional distance measurement techniques, an accelerometer can be used to estimate changes in altitude through double integration. However, this method is prone to biases and integration errors, which can be significant unless mitigated by using additional sensors and sensor fusion algorithms.

For applications such as indoor localization or tracking goods within a warehouse, accurately estimating altitude can be particularly challenging, especially in environments with limited coverage or where ultra-wideband (UWB) anchors are positioned on the same plane. In these scenarios, the ENS220 pressure sensor can offer precise altitude estimates, thereby enhancing the overall localization system.

The ENS220 barometric pressure sensor is not only a feasible alternative to traditional height measurement technologies but also provides unique advantages that are beneficial in a variety of scenarios. While it does have some limitations, its benefits often outweigh these, especially in environments where power efficiency, size, and range of operation are critical factors.

6 Example implementation

Find code resources and drivers on: https://github.com/sciosense/ens220-arduino

7 References

[1] Wikipedia, Hypsometric equation, https://en.wikipedia.org/wiki/Hypsometric_equation

[2] Wikipedia, Vertical pressure variation, https://en.wikipedia.org/wiki/Vertical_pressure_variation

[3] Application note SC-002087-AN 3 /– ENS220 Design Guidelines ENS220-Application-Note-Design-Guidelines.pdf (sciosense.com)

[4] Texas instrument Ultrasonic Sensing Basics application note, https://www.ti.com/lit/an/slaa907d/slaa907d.pdf?ts=1715580395551

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9 Revision information

Table 1: Revision history

Revision	Date	Comment	Page
1.0	2024-12-11	First version	All

Note(s) and/or Footnote(s):

1. Page and figure numbers for the previous version may differ from page and figure numbers in the current revision.
2. Correction of typographical errors is not explicitly mentioned.

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