WÜRTH ELEKTRONIK

ANM003 - Pressure Altimeter using Absolute Pressure Sensor WSEN-PADS

Description	Order code
Sensor in Tape & reel	2511020213301
Sensor Dev-kit (5 pcs. in cut tape)	2511020213381
Sensor Eval-board	2511223013391

Version 1.0

May 5, 2020

Revision history

App note version	Notes	Date
1.0	• Initial release of the app note	May 2020

Abbreviations

Abbreviation	Description
ASIC	Application specific integrated circuit
I^2C	Inter integrated circuit
GNSS	Global navigation satellite system
MEMS	Micro-electro-mechanical system
PCB	Printed circuit board

Contents

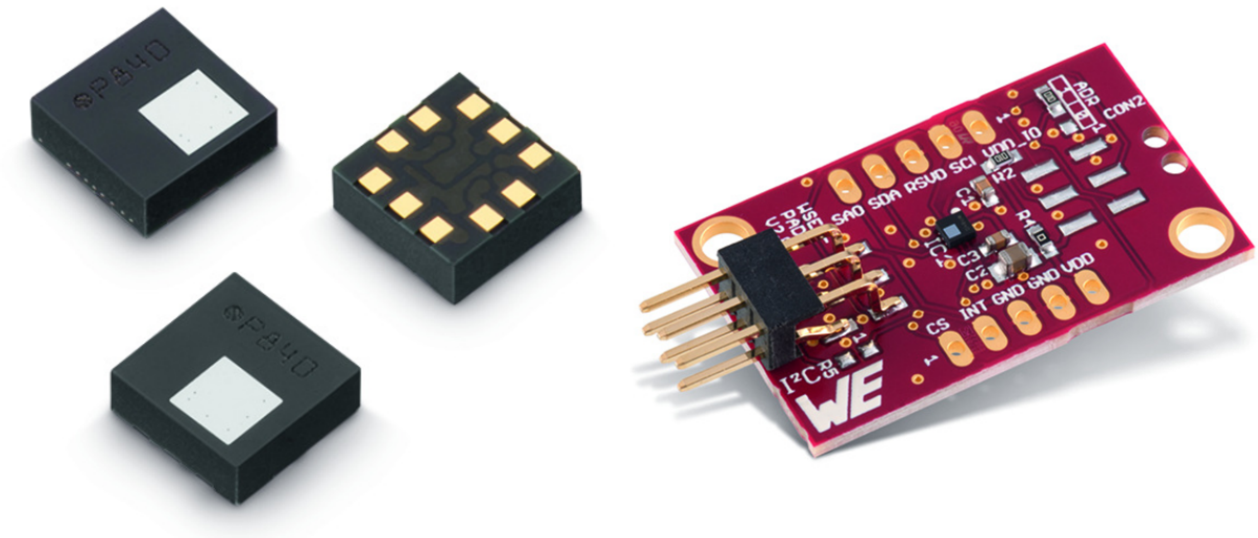
1 Introduction

An altimeter is an instrument that measures the altitude above a fixed level. A number of different types of altimeters exist depending on the measuring principle. These include pressure altimeters, optical altimeters and radar altimeters. The pressure altimeters which measure the atmospheric pressure to infer the altitude, are most widely used device in altimetry.

With the development of MEMS technology, pressure sensors are getting smaller and becoming more affordable. MEMS based pressure sensors have gained popularity in recent years for their altimeter functionality. They are used in various industries for activities such as hiking, climbing, outdoor/indoor localization to enhance GNSS or location-based services, indoor navigation etc.

The absolute pressure sensor (Part nr: 2511020213301) from Würth Elektronik eiSos is a high precision MEMS based digital pressure sensor with an I^{2}C digital interface to provide accurate atmospheric pressure data.

This document describes the altimeter functionality of the absolute pressure sensors from Würth Elektronik eiSos and how the built-in sensor features like filters, offset calibration, temperature compensation etc. help customers to implement the altimeter functionality with high accuracy.



Typical applications of pressure altimeters

- Indoor navigation & floor detection
- Industrial drones
- GNSS enhancement for outdoor navigation
- Smart watches and fitness trackers

2 Atmospheric pressure - Altitude variation

Atmospheric pressure is the pressure generated by the weight of air surrounding the Earth. At low elevations, a square meter on the Earth's surface has greater weight above it than at higher altitudes. As elevation increases, there is less overlying atmospheric mass. So the atmospheric pressure decreases with increasing elevation, whereas atmospheric pressure increases with decreasing elevation. Measured from sea level, atmospheric pressure approximately changes at a rate of 0.125 mbar per meter. However, this is just an approximation, since the air is a compressible medium, there is a non-linear correlation between the atmospheric pressure and the altitude.

The barometric formula provides a correlation between the atmospheric pressure, P (Pa) and the altitude h (m).

$$P = P_0 \cdot \left(1 - \frac{L \cdot h}{c_p \cdot T_0}\right)^{\frac{g \cdot M}{R_0 \cdot L}} \quad (1)$$

Where,

L	=	0.0065 K/m	Temperature lapse rate
g	=	9.80665 m/s^2	Earth-surface gravitational acceleration
M	=	0.0289644 kg/mol	Molar mass of dry air
R_0	=	8.31432 $\frac{N.m}{K \cdot mol}$	Universal gas constant
C_p	=	1004.68506 $\frac{J}{K \cdot kg}$	Constant pressure specific heat

P_0 and T_0 are zero altitude or sea level pressure and temperature respectively. h is the height/altitude in meters.

Lapse rate (L) is the rate at which the temperature varies with the atmosphere. The troposphere (up to 11,000 m) has a linear temperature profile with the altitude. As an average, the International Civil Aviation Organization (ICAO) defines an international standard atmosphere (ISA) with a temperature lapse rate of 6.5 K/km [1], [2]. Hence, the temperature lapse rate as 0.0065 K/m in the troposphere is a good approximation. Rest of the parameters are constant as mentioned.

$$h[m] = \frac{T_0[K]}{0.0065[K/m]} \times \left[1 - \left(\frac{P}{P_0}\right)^{\frac{1}{5.256}}\right] \quad (2)$$

Mean sea level standard pressure is 101.325 kPa and sea level standard temperature is 288.15 K.

Considering mean sea level pressure and temperature, the formula can be simplified as,

$$h[m] = 44330.77 \times \left[1 - \left(\frac{P}{101.325}\right)^{\frac{1}{5.256}}\right] \quad (3)$$

Based on the equation, altitude-pressure relationship can be plotted as shown in the figure 1.

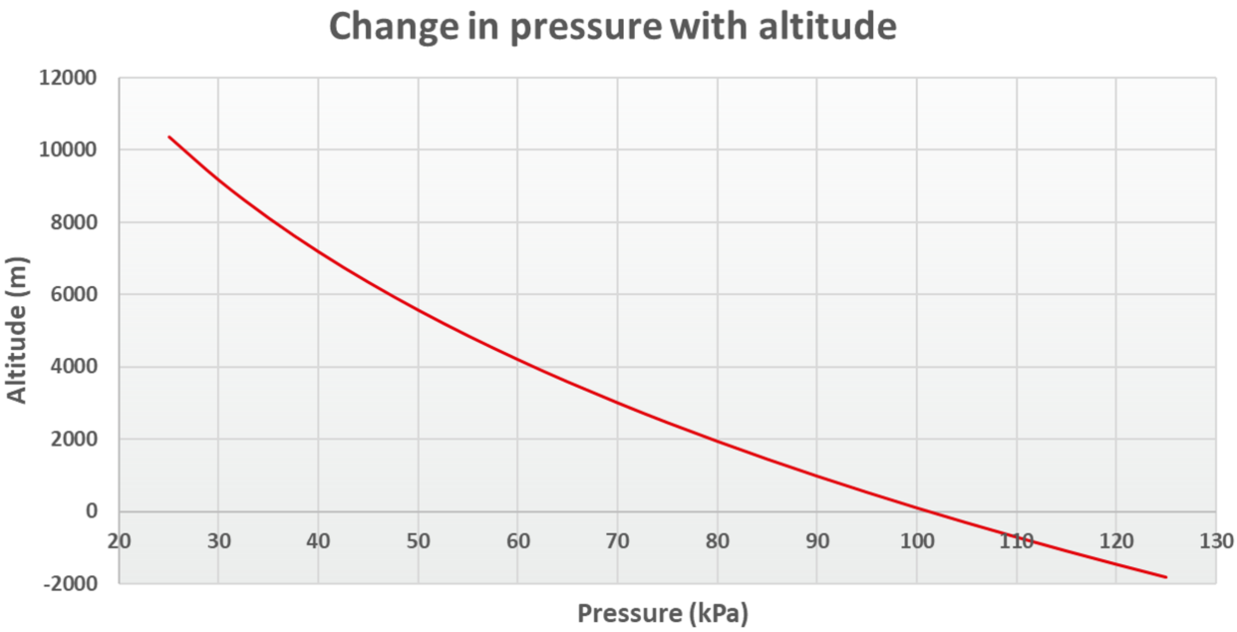


Figure 1: Altitude variation with atmospheric pressure

Co-relation between atmospheric pressure and altitude enables use of absolute pressure sensors as altimeters. A sensor that is calibrated for the whole range of altitude measurement and has capabilities to fix the offset errors can be effectively utilised as an altimeter.

Practically, the altitude of a point can be determined by the method described in the following sections. Used method varies depending on the conditions and available information.

2.1 Reference altitude is known

At a point 'x', whose geographical height/altitude (h_0) is known, the existing pressure at this point can be determined. At a particular altitude h (above or below h_0), pressure P is measured again and applied to the equation (3). Height relative to the point 'x' can be then determined with $h\text{-}h_0$.

2.2 Reference altitude is not known

In order to determine the reference altitude (h_0), first the atmospheric pressure at this point is measured. Reference altitude can be determined from equation-3 by using mean sea level pressure and temperature. Calculated altitude is the absolute height at the point of measurement relative to the mean sea level. After ascent or decent, altitude h can be determined by measuring the atmospheric pressure again from equation (3). This way the relative height ($h\text{-}h_0$) can be determined.

However, special weather conditions are not considered for this formula. Accuracy of the measurement depends on the weather conditions because the atmospheric pressure always changes with the weather. If weather changes during the ascent/decent, resulting relative altitude would be incorrect. In this case, it is recommended to constantly monitor the pressure at reference point h_0.

3 WSEN-PADS as altimeter

Atmospheric pressure and altitude relationship as shown in the figure 1 follows the equation (1). Atmospheric pressure is measured against the vacuum as a reference. As same reference is used in the absolute pressure sensors, they can also be used as altimeters.

WSEN-PADS is a MEMS based absolute pressure sensor that includes a sensing element, analog to digital converter, filters and digital interface that sends the digital pressure data to the host controller through I^2C interface.

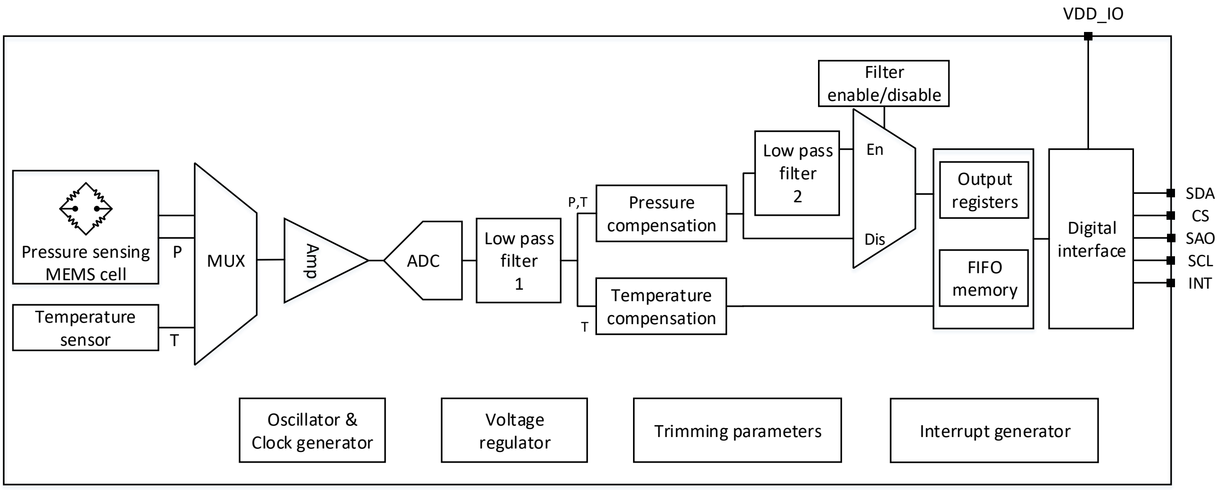


Figure 2: WSEN-PADS block diagram

MEMS based sensing element consists of piezo-resistors on thin Si-diaphragm connected in a Wheatstone bridge configuration. Upon deflection, it measures the applied pressure relative to the vacuum (zero-pressure) sealed inside the cavity of MEMS die during production. Difference between the external pressure and the vacuum causes diaphragm to deflect inward. This mechanical stress changes the bridge resistance and produces voltage proportional to the applied pressure.

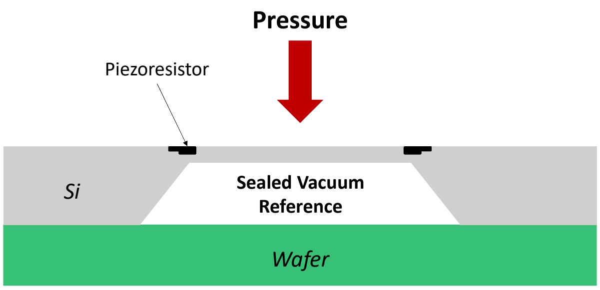


Figure 3: WSEN-PADS sensing element cross section

The ASIC performs amplification, calibration and digital conversion. The ASIC also performs temperature compensation for the measured pressure value through the on-chip temperature sensor. Finally, the digital pressure data can be read through I^2C interface.

3.1 Measurement range and accuracy

Commercially available pressure altimeters have a range between -1000 to 9000 meters with a display resolution of tens of meters. Apart from the resolution, measurement accuracy is also an important factor. Lifetime of the battery depends on the current consumption and the update rate of the sensor.

The absolute pressure measurement range of WSEN-PADS is between 26 kPa and 126 kPa. This corresponds to the altitude range from -1877 meters (below sea level) to 10,109 m (above sea level).

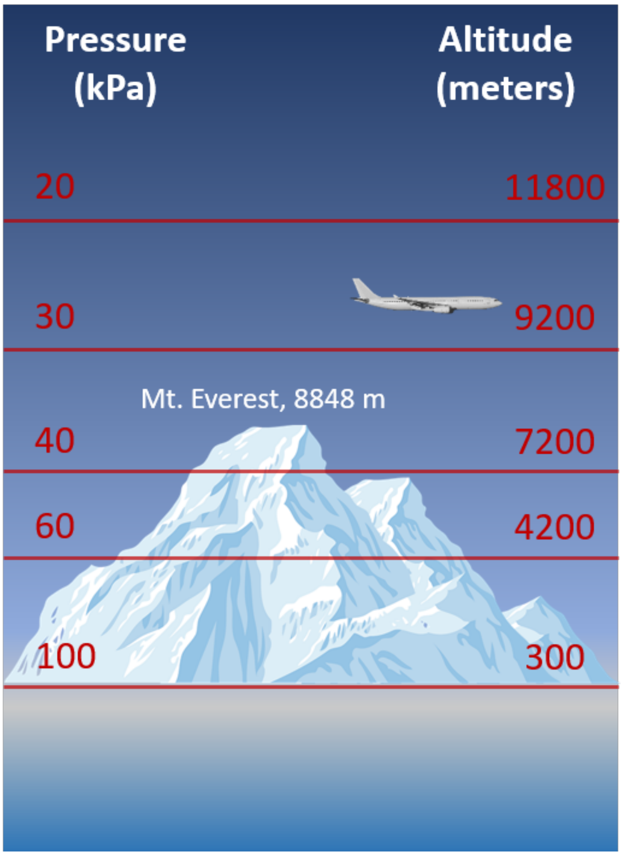


Figure 4: Pressure at particular altitude

The absolute accuracy of the sensor as per the data sheet is ± 100 Pa which corresponds to approximately ± 8 meters in altitude. The absolute accuracy is the output deviation from an ideal transfer function over the operating pressure range. The piezo-resistive sensing element is also sensitive to temperature changes and causes offset errors during pressure measurement. Therefore, real-time temperature compensation of the measured pressure plays an important role in order to achieve high accuracy. WSEN-PADS performs the temperature compensation internally with the on-chip temperature sensor. Apart from this, absolute accuracy is affected by several offset errors which include mechanical stresses (soldering and mounting) or ageing. That's why, relative pressure accuracy is important during altitude measurements. Next section will provide more information on relative accuracy.

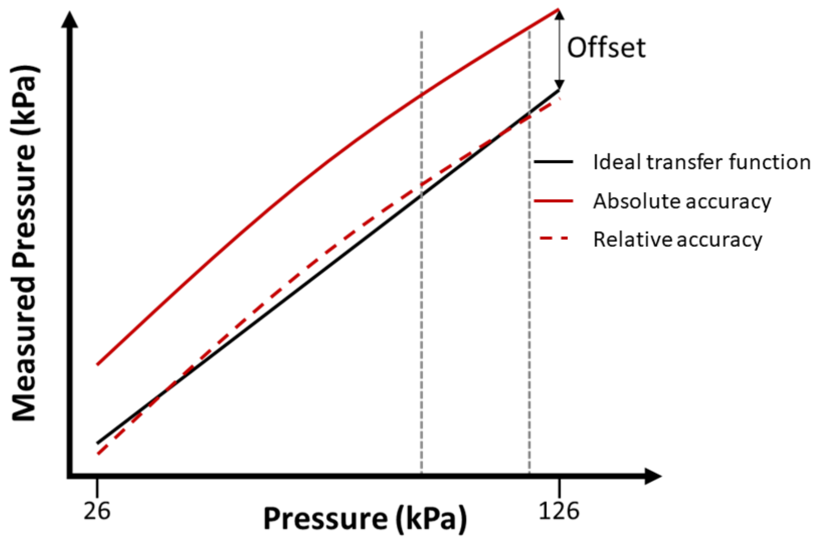


Figure 5: Absolute and relative accuracy

3.2 Relative accuracy

Relative accuracy is defined as the accuracy after removing the offset errors. In the built-in offset calibration registers of the sensor, users can write the correction values to eliminate the offset errors by performing one point calibration. The offset values can be calculated via a calibration device or through known atmospheric pressure at certain locations. As seen in the figure 5, the accuracy is improved due to relative pressure measurement and thus by minimizing the corresponding offset errors. Since the relative accuracy is not affected by the offset errors, it provides much higher altitude accuracy.

By implementing the relative pressure measurement in the altitude determination, further improvement in the accuracy can be achieved. In the practical measurement, a constant temperature and reduced pressure range needs to be considered.

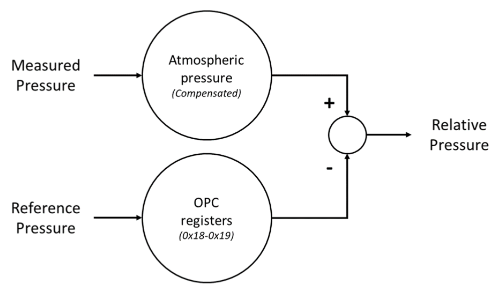


Figure 6: Relative pressure using built-in one point calibration registers

4 Altitude measurement with WSEN-PADS

Altitude is the vertical elevation of an object above a surface. Usually the altitude at a point is defined above the sea level (0 meter). Mean sea level pressure is 101.325 kPa relative to the vacuum (zero pressure reference).

As discussed previously, the atmospheric pressure changes with weather (temperature, wind, rain, clouds). This change will also affect the mean sea level pressure. Sea level is also not constant throughout the surface of the earth and hence the sea level pressure is also not the same everywhere. These factors cause errors and inaccuracies in the altitude measurement. Actual sea-level pressure and temperature must be obtained while calculating the altitude. These information is regularly published in local weather reports via radio, TV, internet or nearby airports.

$$h = \frac{T_0[K]}{0.0065[K/m]} \times \left[1 - \left(\frac{P}{P_0}\right)^{\frac{1}{5.256}}\right] \tag{4}$$

P_0 = 101.325 kPa (mean sea-level pressure at 15° C) and T_0 = 288.15 K.

Initial pressure P_0 can also be calculated by measuring the pressure P at a known altitude h_0 and temperature (T_0) of that point. This pressure value can then be used to determine the further altitude change with respect to the initial altitude h_0.

4.1 Indoor navigation and floor detection

WSEN-PADS can also be implemented in the indoor navigation. Typical RMS noise of 0.75 Pa corresponds to approximate 6-8 cm in relative height. This is the minimum change in pressure or altitude that can be reliably measured. This enables the use of sensors in floor detection as well as mezzanine detection.

Pressure and temperature at the initial point can be measured from the sensor. During the ascent or descent the change of pressure can be monitored to determine the current height (h) from the equation (4). P_0 and T_0 are the pressure and temperature at the initial point with altitude h_0=0. In these measurements, the accuracy depends on the weather conditions and the barometric pressure at the initial/reference point. Changes in the barometric pressure during the ascent/descent should be considered during the height calculations. Optionally a second absolute pressure sensor can be placed at the initial/reference position that measures the real-time barometric pressure.

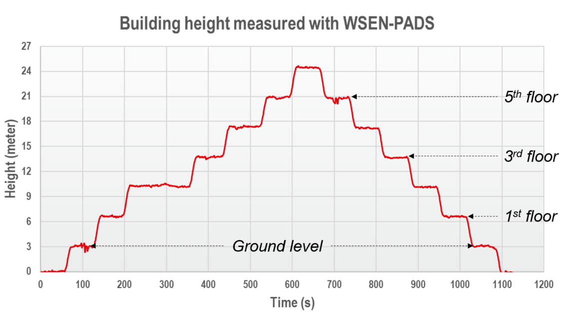


Figure 7: Building height measured with WSEN-PADS

In the figure 7, WSEN-PADS was used to measure the height of each floor of a 6 storey building with a basement. The sensor was placed in an elevator that stopped on each floor. As seen in the figure 7, height of each floor was calculated with help of the barometric formula. A constant reference temperature is assumed. As for a short period of time and relatively small altitude change, the temperature changes can be neglected.

WSEN-PADS has special features integrated that supports the altitude measurements. By using the AUTOREFP or AUTOZERO feature along side the noise reduction filter, very accurate relative height measurements are possible with WSEN-PADS. It is also possible to use the calibration registers (0x18 - 0x19) in order to remove the offset errors due to residual stress after the reflow solder.

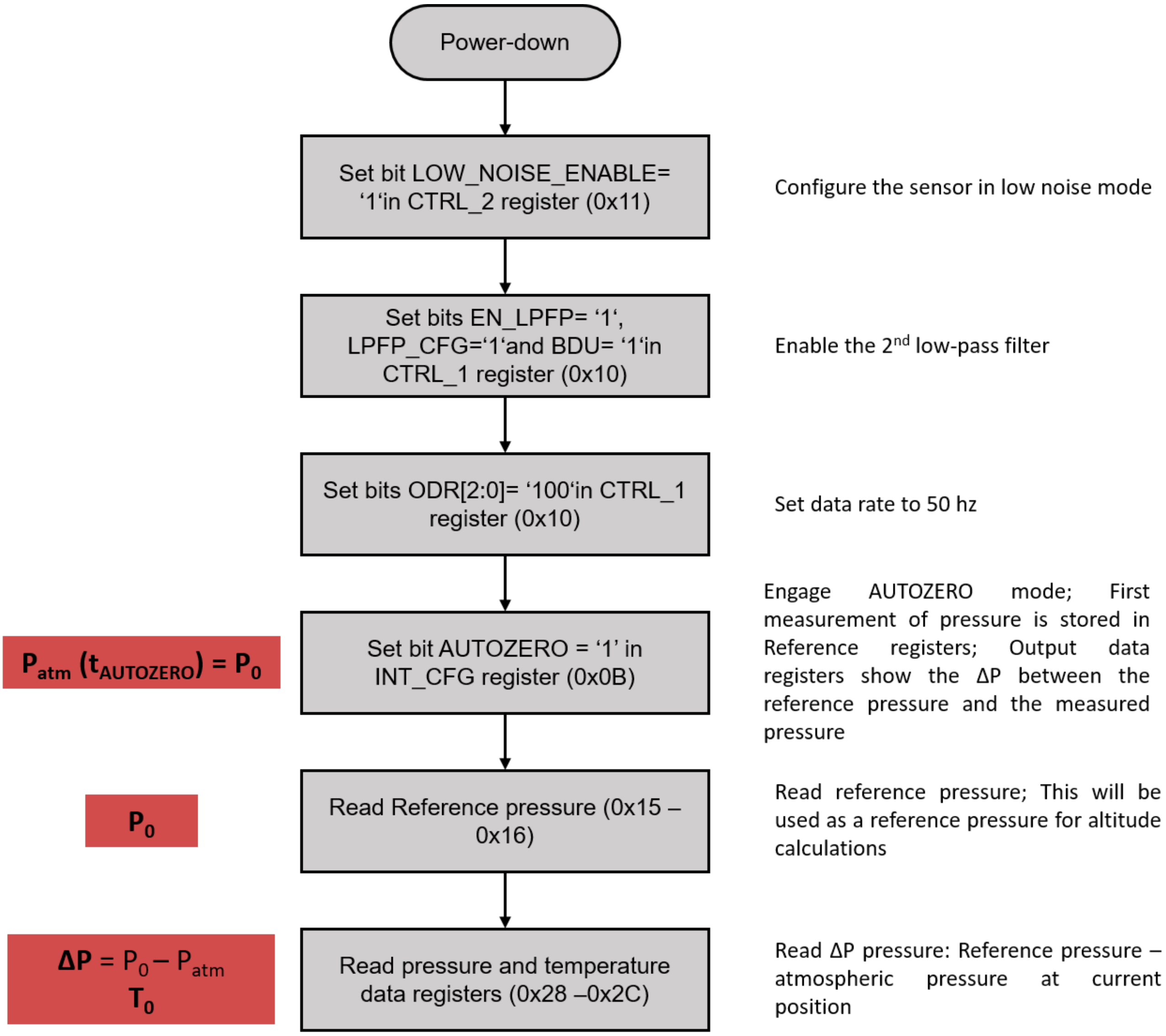


Figure 8: Building height measured with WSEN-PADS

For detailed information about the AUTOREFP/AUTOZERO function and how it can be implemented, please refer to the user manual of WSEN-PADS (Part nr. 2511020213301).

When the built-in AUTOZERO feature is engaged, first instantaneous measurement of pressure is stored in the reference pressure registers. Output data register show the relative pressure which is the pressure difference between the stored reference pressure. The relative height can be measured with the following equation (5)

$$h = \frac{T_0[K]}{0.0065[K/m]} \times \left[1 - \left(\frac{\Delta P + P_0}{P_0}\right)^{\frac{1}{5.256}}\right] \tag{5}$$

Similarly, AUTOREFP function can also be used to determine the altitude. When the AUTOREFP feature is engaged, first measurement of pressure is stored in the reference pressure registers. Current temperature and atmospheric pressure can be read via output data registers. Current atmospheric pressure can be used to determine the relative height with respect to the point where the reference pressure was obtained.

5 Summary

Altitude can be accurately determined by measuring the atmospheric pressure. The weather changes constantly and could have a large effect on the end application or whole system. A sensor with built-in functionalities and on chip offset compensation helps in eliminating the inaccuracies caused by such changes. WSEN-PADS has integrated calibration algorithms and data logging features. Multiple selectable data rates, user defined interrupt and noise reducing filter settings of the sensor enables highly accurate pressure and altitude measurements.

This application note provided a brief idea about how absolute pressure sensors can be used to measure the altitude above sea level as well as relative height above a fixed point. Various applications such as floor detection for window-washers or construction workers, weather stations and GNSS accuracy enhancement etc. can benefit from these features and functionality.

References

[1] International Organization for Standardization; *Standard Atmosphere*; 1975; ISO 2533:1975.

[2] Manual of the ICAO Standard Atmosphere (extended to 80 kilometres) (3rd edition); *International Civil Aviation Organization*; 1993; ISBN 978-92-9194-004-2. Doc 7488-CD.

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List of Figures

References

[1] International Organization for Standardization; *Standard Atmosphere*; 1975; ISO 2533:1975.

[2] Manual of the ICAO Standard Atmosphere (extended to 80 kilometres) (3rd edition); *International Civil Aviation Organization*; 1993; ISBN 978-92-9194-004-2. Doc 7488-CD.

more than you expect

Internet of Things

Monitoring & Control

Automated Meter Reading

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