Freescale Semiconductor
Application Note

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Pressure Altimetry using the MPL3115A2

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Contents

1 Introduction

An altimeter is an instrument used to measure the altitude of an object above a fixed level. One of the most common types of altimeters is a pressure altimeter. A pressure altimeter measures atmospheric-pressure data to determine the altitude. They are widely used in aviation, and in association with topographical and geographical activities. With the development of pressure-sensor technology, pressure altimeters are becoming more affordable, sophisticated and used in our daily life for activities such as hiking, climbing, outdoor/indoor localization for GPS assist, E911 or location-based services.

Freescale's Xtrinsic MPL3115A2 is a precision altimeter and employs a MEMS pressure sensor with an I^2C interface to provide accurate pressure or altitude data. It has very low-power consumption, smart features and requires no data processing for mobile devices, medical and security applications.

This application note answers some frequently asked questions in pressure-altimeter applications with the altitude under 11 km above sea level (the range of the MPL3115A2). This document also shows how to use the device’s smart features to develop feasible and effective product solutions.

1.1 Related Documentation

The MPL3115A2 device features and operations are described in a variety of reference manuals, user guides, and application notes. To find the most-current versions of these documents:

1. Go to the Freescale homepage at:

   http://www.freescale.com/

2. In the Keyword search box at the top of the page, enter the device number MPL3115A2.
3. In the Refine Your Result pane on the left, click on the Documentation link.

2 Basic Knowledge and Terminology

Altitude is the height of a point or object above a reference level in the vertical direction, usually above sea level. In geography, the term **Elevation** is often preferred for this usage.

Mean Sea Level (MSL) is a measure of the average height of the ocean's surface, such as the halfway point between the mean high tide and the mean low tide. It is used as a standard in reckoning land elevation.

Pressure altitude is the indicated altitude when an altimeter is set to an agreed baseline pressure setting at 101.325 kPa which is equivalent to the air pressure at mean sea level.

Pressure (P) is the force (F) per unit area (A) applied in a direction perpendicular to the surface of an object. **Atmospheric pressure** is caused by the weight of air above the measurement point.

$$P = \frac{F}{A}$$

The **Standard atmosphere** is a hypothetical vertical distribution of atmospheric properties which, by international agreement, is roughly representative of year-round, mid-latitude conditions. Also the standard atmosphere (symbol: atm) is a unit of pressure and is defined as being equal to typical air pressure at mean sea level.

$$1\ \text{atm} = 101.325\ \text{kPa} = 1013.25\ \text{mbar}\ (\text{or hPa}) = 760\ \text{mmHg} = 29.92\ \text{inHg} = 14.696\ \text{psi}$$

The **U.S. Standard Atmosphere** is a series of models that define values for atmospheric temperature, density, pressure and other properties over a wide range of altitudes. The first model, based on an existing international standard, was published in 1958 by the U.S. Committee on Extension to the Standard Atmosphere, and was updated in 1962, 1966, and 1976.

3 Altitude Atmospheric-Pressure Variation

Low-pressure areas have less atmospheric mass above their location, whereas high-pressure areas have more atmospheric mass above their location. Likewise, as elevation increases, there is less overlying atmospheric mass, so that atmospheric pressure decreases with increasing elevation, whereas atmospheric pressure increases with decreasing elevation.

Atmospheric pressure varies smoothly from the Earth's surface to the top of the mesosphere, at an altitude of 80–90 km. Although the atmospheric pressure changes with the weather, NASA has averaged the conditions for all parts of the earth year round. Table 1 lists worldwide averaged temperature and atmospheric pressure at each altitude from -800m to 1100m provided by *U.S. Standard Atmosphere, 1976.*

http://ccmc.gsfc.nasa.gov/modelweb/atmos/us_standard.html).

Table 1. Temperature and pressure for altitudes

h (m)	T (°C)	P (Pa)	h (m)	T (°C)	P (Pa)	h (m)	T (°C)	P (Pa)
-800	20.2	111,312	3200	-5.8	68,344	7200	-31.8	39,918
-600	18.9	108,744	3400	-7.1	66,615	7400	-33.1	38,800
-400	17.6	106,223	3600	-8.4	64,922	7600	-34.4	37,709
-200	16.3	103,751	3800	-9.7	63,264	7800	-35.7	36,642
0	15.0	101,325	4000	-11.0	61,640	8000	-37.0	35,600
200	13.7	98,945	4200	-12.3	60,051	8200	-38.3	34,582
400	12.4	96,611	4400	-13.6	58,494	8400	-39.6	33,587
600	11.1	94,322	4600	-14.9	56,971	8600	-40.9	32,616
800	9.8	92,076	4800	-16.2	55,479	8800	-42.2	31,668
1000	8.5	89,875	5000	-17.5	54,020	9000	-43.5	30,742
1200	7.2	87,716	5200	-18.8	52,592	9200	-44.8	29,839
1400	5.9	85,599	5400	-20.1	51,194	9400	-46.1	28,957
1600	4.6	83,524	5600	-21.4	49,827	9600	-47.4	28,096
1800	3.3	81,489	5800	-22.7	48,489	9800	-48.7	27,256
2000	2.0	79,495	6000	-24.0	47,181	10,000	-50.0	26,436
2200	0.7	77,541	6200	-25.3	45,901	10,200	-51.3	25,637
2400	-0.6	75,626	6400	-26.6	44,650	10,400	-52.6	24,857
2600	-1.9	73,749	6600	-27.9	43,426	10,600	-53.9	24,097
2800	-3.2	71,910	6800	-29.2	42,230	10,800	-55.2	23,355
3000	-4.5	70,109	7000	-30.5	41,061	11,000	-56.5	22,632
Where: h is altitude; T is temperature; P is atmospheric pressure								

Equation 1 is used for computing atmospheric pressure (P, in Pa) at a different altitude (h, in m) below 11 km.

$$P = P_0 \cdot \left(1 - \frac{L_0 - h}{T_0}\right)^{\frac{g_0 \cdot M}{R^* \cdot L_0}} \quad \textbf{\textit{Eqn. 1}}$$

where:

Symbol	Value	Unit	Description
P_0	101,325	Pa	Sea-level standard atmospheric pressure
L_0	0.0065	K/m	Temperature lapse rate from sea level to 11 km
T_0	288.15	K	Sea-level standard temperature
g_0	9.80665	m/s^2	Sea-level gravitational acceleration
M	0.0289644	kg/mol	Mean-molecular weight of air
R*	8.31432	N·m/(K·mol)	Universal gas constant

By inserting these parameters into Equation 1, we get the simplified Equation 2 for atmospheric-pressure calculation based on known altitude.

$$P = P_0 \cdot \left(1 - \frac{h}{44330.77}\right)^{5.255876} \quad \textbf{\textit{Eqn. 2}}$$

Equation 3 is used for altitude calculation based on known atmospheric pressure after the conversion to Equation 2.

$$h = 44330.77 \cdot \left[1 - \left(\frac{P}{P_0}\right)^{0.190263}\right] \quad \textbf{\textit{Eqn. 3}}$$

According to Equation 3, we can determine the altitude value with an accurate atmospheric-pressure measurement.

4 Working Principle

Atmospheric pressure is zero-referenced against a perfect vacuum. Due to the same reference applied in absolute-pressure measurement, the absolute-pressure sensor is normally used to determine the altitude as the absolute (or atmospheric) pressure measured in comparison on the sea-level pressure. This absolute-pressure sensor is called a *Pressure Altimeter.*

Freescale's MPL3115A2 device is a precision altimeter that includes a sensing element, analog- and digital-signal processing and an IC interface able to take the information from the sensing element and provide a signal to the host through an I^2C serial interface. The block diagram is shown in Figure 1.

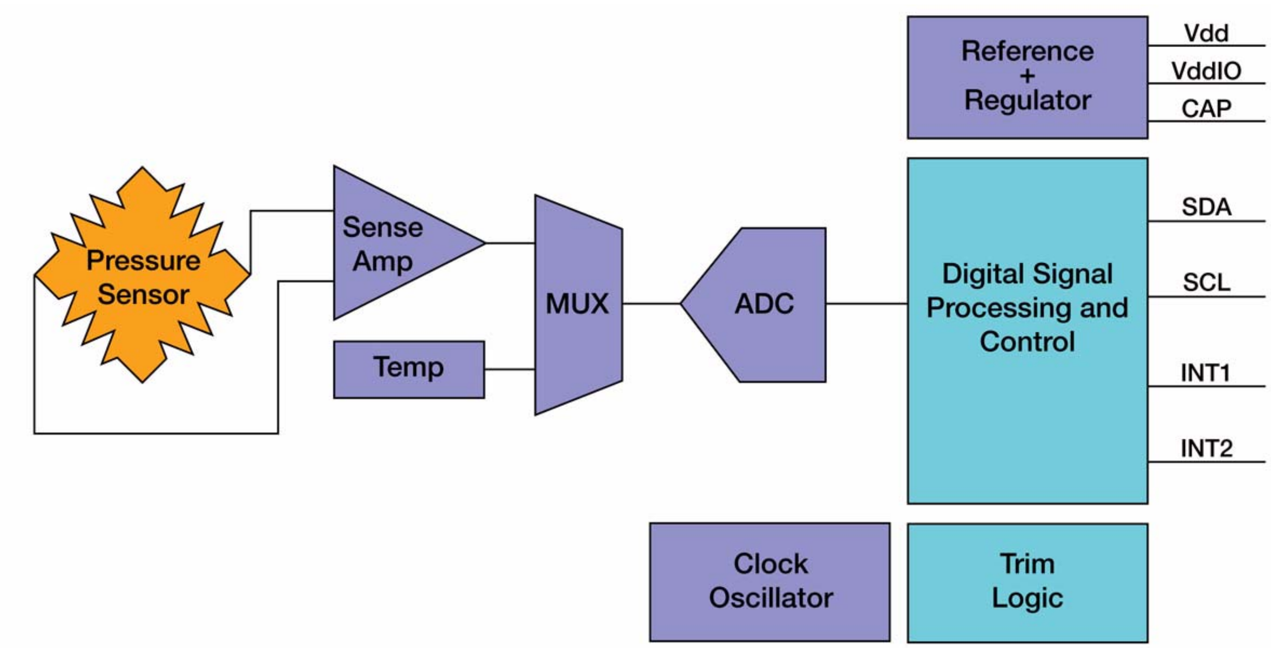

Figure 1. MPL3115A2 pressure-sensor block diagram

The absolute-pressure sensing element of the MPL3115A2 altimeter is based on the piezoresistive effect of strain resistance to detect applied atmospheric pressure (P1) relative to a zero-pressure reference (vacuum pressure) sealed inside the reference chamber of the die during manufacturing.

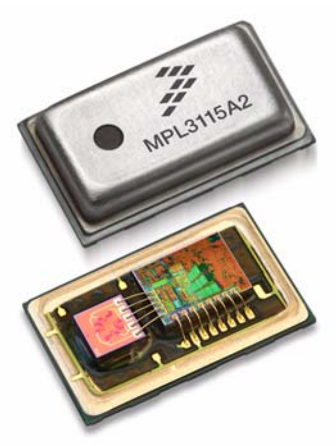

Figure 2. Zero-pressure reference (vacuum pressure) sealed inside the reference chamber

Figure 3 shows the cross section of the absolute-pressure sensing element of the MPL3115A2. The difference in positive pressure between P1 and vacuum pressure causes the diaphragm to deflect inward. The four piezoresistive strain-gauge resistors located in the diaphragm itself are connected as a Wheatstone bridge, which detects the deflection of the diaphragm as a mechanical stress and provides a voltage output. This voltage output is proportional to P1 and the supply voltage, which will be sampled by the dedicated ASIC of the MPL3115A2 for further processing, such as signal amplification and ADC conversion. Also the ASIC performs oversampling trim compensation, data-path calculations and I^2C port control to provide final digital outputs.

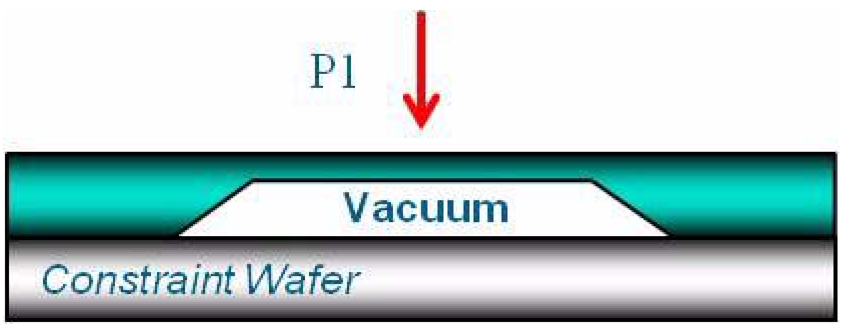

Figure 3. Cross section of absolute pressure-sensing element

Depending on the operation mode selected, the MPL3115A2 can directly output 20-bit atmospheric-pressure data in Pascals or 20-bit altitude data in meters. Atmospheric pressure can be resolved in fractions of a Pascal and altitude can be resolved in fractions of a meter. The internal conversion of atmospheric pressure to altitude is based on Equation 3 derived from *U.S. Standard Atmosphere*, *1976*. Also, 12-bit temperature data in degree celsius is provided at the same time, as well as for internal compensation of the pressure sensor.

5 Measurement Range

The absolute-pressure measurement range (operational pressure range) of the MPL3115A2 is from 20 kPa to 110 kPa and the corresponding altitude range is from -698m to 11,775m. The calibrated pressure range is from 50 kPa to 110 kPa which corresponds to an altitude range from -698m to 5574m. Within the calibrated pressure range, the accuracy of the MPL3115A2 should meet the requirements of the specification described in the data sheet. If the measured pressure is out of this range, but within the operational pressure range, the sensor still functions reasonably well, but does not meet all accuracy requirements in the data sheet.

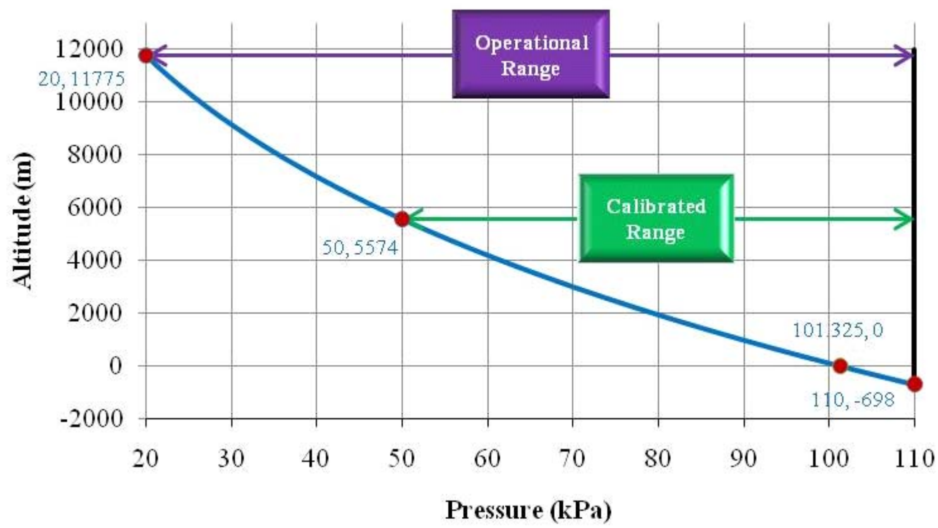

Figure 4. Measurement range of the MPL3115A2

The measurement range of the MPL3115A2 can cover all areas on land that could be reached during hiking and climbing with a handheld device, and some are listed as below:

- The highest point on earth is the peak of Mount Everest at 8848 meters above sea level.
- The highest city in the world is Wenzhuan at 5019 meters above sea level.
- The highest city in the United States is Leadville at 3094 meters above sea level.
- The lowest point on earth is the surface of Dead Sea at 422 meters below sea level.

6 Measurement Accuracy

The absolute accuracy is the maximum output deviation from a straight line which is defined by an ideal transfer function over the operating pressure range (Figure 5).

The absolute accuracy of the MPL3115A2 provided by the data sheet is ±0.4 kPa within the pressure range from 50 to 110 kPa and over the temperature range from -10 to 70°C, equivalent to about ±33m within 6273m altitude range.

The absolute measurement method is affected by several offset errors resulting in P_{off}. Sources of offset errors could be due to device-offset variation (trim errors), mechanical stresses (mounting stresses), shifts due to temperature and aging. The MPL3115A2 is factory calibrated for sensitivity and offset for both temperature and pressure measurements and the default values are used on power up. Using internal-offset correction registers, users can adjust the offset values to easily remove these errors after power up for the highest possible accuracy. Further calibration overrides the factory settings and does not affect the factory-calibration values. Users can directly write the correction values of pressure, altitude and temperature into respective user-offset registers (OFF_P, OFF_H and OFF_T). These values will be used by the internal algorithm during the output calculation.

The relative accuracy is considered as the absolute accuracy without the offset errors. One specification of the relative accuracy of the MPL3115A2 is ±0.1 kPa (about ±8m altitude) during the temperature change from -10°C to 50°C at any constant pressure (between 50 kPa and 110 kPa). The other specification is ±0.05 kPa (about ±4m altitude) during the pressure change from 70 to 110 kPa at any constant temperature (between -10°C and 50°C). As depicted in Figure 5, the output errors are reduced due to specified relative-measurement conditions on pressure or temperature, and the removal of related offset errors. Therefore, the relative-measurement method is not affected by the offset errors.

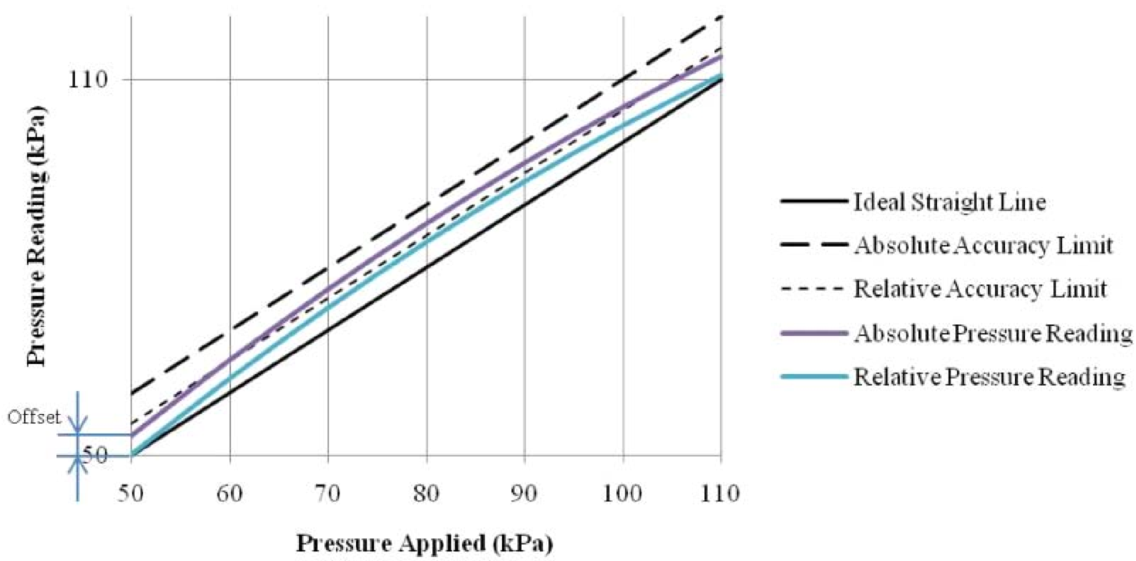

Figure 5. Absolute accuracy versus relative accuracy

According to the above results, a further improvement on measurement accuracy is also possible by applying the relative-measurement method in some actual applications.

For example, the absolute-measurement error at ±33m altitude is reasonable at an altitude above 6000m (such as mountaineering) from the foot to the summit. But it is unacceptable in some short distance or short interval applications, such as floor detection. Users can utilize the MPL3115A2 altitude data user-offset register (OFF_H) to implement the relative measurement by altitude-reference adjustment. Users can write the altitude value at the start point into the offset register as the reference. At that moment the altitude output becomes 0m. During the application, any altitude value at the other points will be compared with this reference and the sensor outputs the vertical distance between these two altitude points. The common offset shifts, caused by weather variation on both points, are removed by this processing. This greatly improves the measurement's accuracy. The most important thing in this case is that the measurement range is also reset by the altitude value at the start point and end point. In relative measurements, the measurement accuracy will be changed with the measurement range changing. As depicted in Figure 6, combined with offset removing, the measurement error becomes smaller with the measurement range reducing. This ensures effective and sufficient accuracy for each application case.

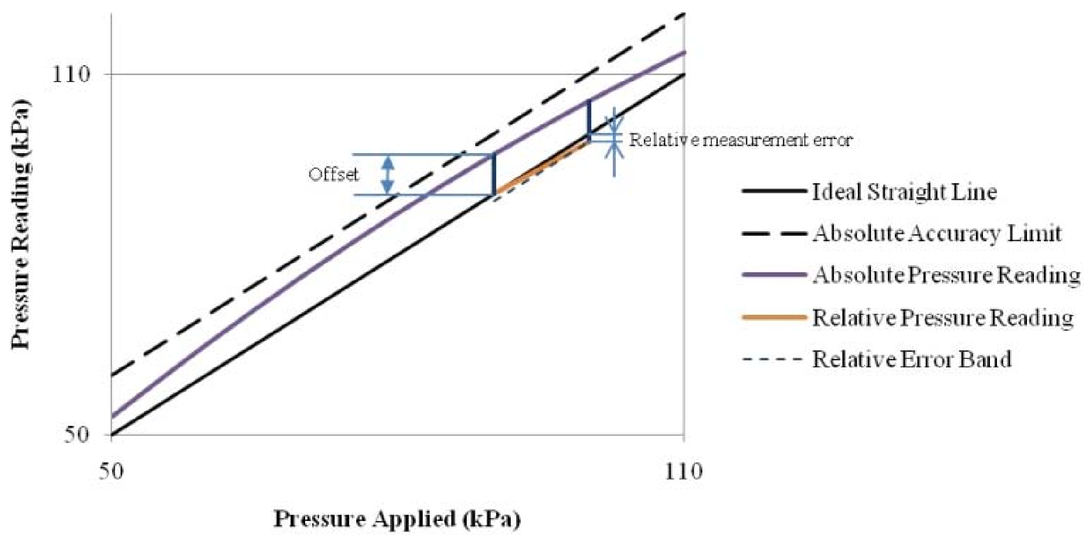

Figure 6. Relative-measurement error

Due to the large measurement range of the MPL3115A2, covering all types of altitude applications, the relative-measurement method has important practical significance to smaller (pressure and temperature) range detection. The minimum relative-measurement error will depend on the resolution of the sensor, which is the minimum change of pressure or altitude that can be reliably measured. The MPL3115A2 provides a stable, 30-cm output resolution in altitude and enables building level certainty, including mezzanine (1/2 level).

7 Effect in Applications

The altitude of one point is the height above zero meters at sea level, and the sea-level pressure is defined as 101.325 kPa relative to a zero-pressure reference, as shown in Figure 6.However, sea level is not a constant over the surface of the Earth.

For instance, mean sea level at the Pacific end of the Panama Canal stands 20 cm higher than at the Atlantic end. Also the actual sea level pressure in world is not same, and is always changed with weather variations. Weather is the state of the atmosphere. Most weather phenomena occur in the troposphere, the average depth of which is approximately 17 km in the middle latitudes. Common weather phenomena include wind, cloud, rain, snow, and fog. Weather variations will affect not only sea level pressure but also atmospheric pressure, temperature and moisture. These changes will cause errors in altitude measurement.

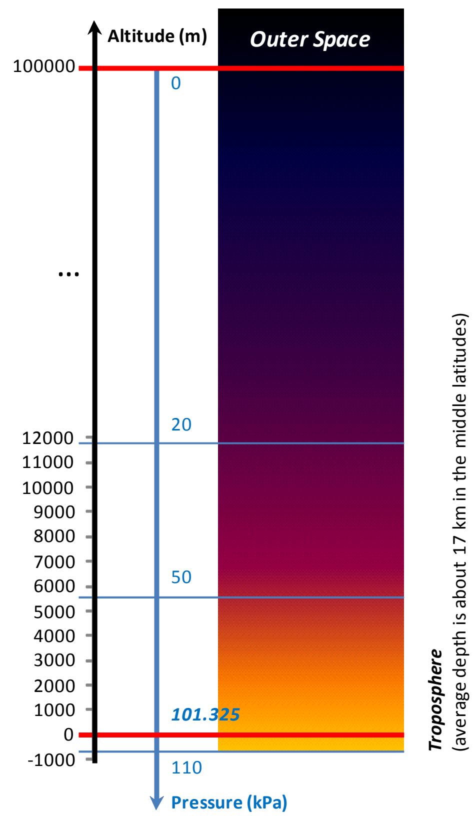

Figure 7. Pressure Altitude

In order to remove the errors caused by sea-level pressure changes, it is very important to obtain the actual sea-level pressure (P_0). Normally it is given in weather reports on radio, television, newspapers and the internet. The barometric pressure input register (BAR_IN) provided by the MPL3115A2 is used for the user's input of P_0 to match the local weather report. Due to register-bit limitations, the default value is 101,326 Pa, rather than 101,325 Pa, but that will not affect the altitude-output accuracy. After power up, users can write the value of P_0 into this register to replace the default value as the pressure reference at sea level for internal altitude calculation.

The value of P_0 can be worked out using the atmospheric pressure (P) measured at a given altitude (h), such as a trail junction or peak marked on a topographical map. Users can insert the value of P and h into Equation 2 on page 4 for the calculation, and then write the result of P_0 into the register (BAR_IN) for internal altitude calculation.

$$P = P_0 \cdot \left(1 - \frac{h}{44330.77}\right)^{-5.255876} \qquad \textbf{Eqn. 4}$$

Sea-level shift is looked at as sea-level pressure change, and therefore the errors caused by the changes of sea level can also be removed by the reverse calculation of P_0.

As listed in Table 1 on page 3, the temperature of atmosphere changes with altitude. The altitude algorithm provides the basic solution with the temperature lapse rate (L_0) and sea-level standard temperature (T_0) introduced, as in Equation 1 on page 4. L_0 is the rate of decrease of temperature with altitude from sea level to 11 km, and is defined as 0.0065 K/m in *U.S. Standard Atmosphere*. T_0 is defined as 288.15K. With both data adopted, the equation enables the dynamic-altitude detection below 11 km. However, the effectiveness of this algorithm is based on correct atmospheric-pressure measurement.

In actual applications, the atmospheric-pressure measurement is affected by temperature variations caused by altitude and weather changes. The piezoresistive sensor has excellent linearity in pressure measurement, but is sensitive to temperature variations. Therefore, the local real-time temperature compensation for the atmospheric-pressure output plays an important role. The MPL3115A2 performs temperature compensation internally with inside temperature sensor for accurate pressure measurement. Also, the temperature offset can be compensated by temperature data user-offset registers (OFF_T) after power up.

The use of the stainless steel lid on the MPL3115A2 allows the sensor to reach a quick thermodynamic equilibrium with its environment. Because of this, actual applications must provide a smooth air path between the sensor and atmosphere to reduce the temperature effect from the other devices running around the sensor. A smooth air path also is a basic requirement for atmospheric-pressure measurement and ensures accurate altitude output.

As we know the standard atmosphere contains no moisture, but the humidity also will affect the atmospheric pressure. As mentioned in the section of “Measurement Accuracy,” using relative-measurement method, especially utilizing altitude data user-offset register (OFF_H), the effect caused by humidity and suspended particles can be reduced or even removed.

8 Summary

Altitude can be determined based on the measurement of atmospheric pressure. But the atmosphere is a chaotic system, so small changes to one part of the system can grow to have large effects on the system as a whole. The *U.S. Standard Atmosphere* is based on many assumptions, including ideal gas behavior, and constant molecular weight. Therefore, in pressure altimetry, the intelligent-pressure sensor is more helpful in removing the effects of various conditions and improving the altitude measurement accuracy with smarter features.

Like the other members of the Xtrinsic sensor family, the MPL3115A2 is an intelligent sensor with integrated-data calculation and logging capabilities. Multiple user-programmable, power-saving, interrupt and autonomous data-acquisition modes are available. Internal processing removes compensation tasks from the host MCU system. The MPL3115A2 is offered in a 5 mm by 3 mm by 1.1 mm LGA package and specified for operation from -40°C to 85°C. The package is a surface mount with a stainless steel lid and is RoHS compliant. Please refer to the MPL3115A2 data sheet for updated and detailed information.

Figure 8. LGA package, 5 mm by 3 mm by 1.1 mm

The data-oversampling ratio can be set to balance current consumption and resolution. Typical active supply current is 40 µA per measurement-second for a stable 30 cm output resolution. It is ideal for portable applications when the sensor operates at 8.5 µA in low-power mode at 1 Hz, for example Smartphones, tablets, and leisure/sports equipment.

One of the typical applications is outdoor/indoor localization in location-based services and GPS-dead reckoning. GPS receivers can determine altitude by satellites but it is not precise or accurate enough and may be unavailable when one is deep in a canyon, or may give wildly inaccurate altitudes when all available satellites are near the horizon. It is more reliable to provide location information by using pressure altimeter in hiking and climbing with a topographic map. A more perfect navigation solution could be provided when fusing the MPL3115A2 data with the information from accelerometers, gyros and magnetometers.

The MPL3115A2 can also be used in weather stations, appliances, security and safety devices, assisted breathing and sleep-apnea systems. The target applications include consumer, industrial and medical fields.

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