Altimeter and Barometer System

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INTRODUCTION

With smaller packages and lower costs, pressure sensors can be designed into more consumer applications. This document describes a reference design for a digital barometer and altimeter using the MPXM2102A pressure sensor in the low cost MPAK package, a quad op-amp, and the MC68HC908QT4 microcontroller. This system continuously monitors the barometric pressure and compares it to previous pressure readings to update altitude and weather predictions. This reference design enables the user to evaluate a Freescale Semiconductor, Inc. pressure sensor for barometer, personal weather station and altimeter applications. This reference design also allows customers to evaluate barometer pressure readings obtainable from the MPXM2102A sensor for watches or GPS systems with this feature. In addition, many systems require barometric pressure data to correct system response errors. This application note describes the reliability and accuracy that our sensors can provide in this system.

SYSTEM DESIGN

Pressure Sensor

The barometer/altimeter system requires a pressure sensor that has a pressure range of 64 kPa to 105 kPa. Freescale Semiconductor, Inc. has a broad portfolio of silicon piezo-resistive pressure sensors. They provide a very accurate and linear voltage output directly proportional to the applied pressure. By evaluating the application design and cost, the right pressure sensor can be selected from our portfolio.

Figure 1. Pressure Sensor

There are three types of pressure measurements: gauge, absolute, and differential. Since this reference design measures changes in ambient pressure, we need a known pressure reference. Therefore, an absolute pressure sensor was selected. Freescale offers three levels of integration: un-compensated, compensated, and integrated. Since there can be large temperature changes from one elevation to another the sensor for this reference design needs to be offset calibrated and temperature compensated. Therefore a compensated sensor was selected requiring external amplification circuitry. However, integrated solutions such as the MPXM5100A, can also be considered, thereby eliminating the need for the external amplification circuitry.

Knowing the range of pressure, the type of pressure measurement, and the level of integration required for this application, the MPXM2102A sensor was selected. The sensor has both temperature compensation and calibration circuitry on the silicon and is capable of producing a linear output voltage in the range of 0 to 100 kPa, but can be pushed further up to 105 kPa with linear results. The characteristics of this sensor are described in greater detail in Table 2. A 5-volt supply was used throughout the circuit to power the components. Since the MPXM2102A is ratio metric, meaning the output voltage changes linearly with the supply voltage, the sensor will have a full scale span of 20 mV instead of the specified 40 mV at a 10 V supply. The calculation of the full scale span is shown below:

$$(V_{S\ actual}/V_{S\ spec}) \times V_{OUT\ full\text{-}scale\ spec} = V_{OUT\ full\text{-}scale}$$

$$(5.0\ V/\ 10\ V) \times 40\ mV = 20\ mV$$

One of the most important decisions for a pressure application is the packaging. Freescale has a large offering of pressure packaging options. To minimize the space of a final application, the MPAK package was selected. A non-ported MPAK is the ideal pressure sensor package for hand held GPS units or altimeter watches due to its small size. However, a ported MPAK package can also be selected, allowing a tube to be attached to the port for testing and demonstration purposes.

Figure 2. MPXM2102A Case 1320A-02

freescale
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Table 1. MPXM2102A Operating Characteristics

Characteristic		Symbol	Min	Typ	Max	Unit
Pressure Range		P_{OP}	0	—	100	kPa
Supply Voltage		V_S	—	10	15	Vdc
Supply Current		I_O	—	6.0	—	mAdc
Full Scale Span		V_{FSS}	38.5	40	41.5	mV
Offset		V_{off}	-1.0	—	1.0	mV
			-2.0	—	2.0	
Sensitivity	MPX2102D Series		—	0.4	—	MV/kPa
	MPX2102A Series	$\Delta V/\Delta P$				
Linearity	MPX2102D Series		—	-0.6	—	0.4	%V_{FSS}
	MPX2102A Series		—	-1.0	—	1.0	

Amplifier Selection and Amplifier Induced Errors

The main goal of the signal conditioning circuit is to convert the MPX2102A differential output to a single-ended, ground-referenced output. The differential output is extremely small for the MCU to process so a conditioning circuit also needs to provide amplification.

This reference design has a barometric pressure range of 64 kPa to 105 kPa. The output of the sensor is ratiometric to the supply voltage and the supply voltage is 5.0 V, the FSS, Sensitivity, and Offset are 5.0 V/10 V, or half, of the specified values at a 10 V supply. Using these calculated sensitivity and offset ranges, the lowest and highest possible values were calculated.

V_{OUT} = (Applied Pressure * Sensitivity) ± Offset

V_{OUT} at 64 kPa = 64 kPa * 0.2 mV/kPa — 1 mV = 11.32 mV

V_{OUT} at 105 kPa = 105 kPa * 0.2 mV/kPa + 1 mV = 21.0 mV

These values were found to be 11.32 mV to 22.79 mV differential output from the sensor.

Two-Stage Design

This two-stage design level shifts the differential output voltage of the sensor by subtracting an offset voltage from each of the sensor outputs, then uses a differential amplification as shown in Figure 2.

After the first stage of amplification, the output of op-amp A is:

V_A = (1+R8/R6) x V_4 – (R8/R6) x V_S(1)

= (1+10/4.42k) x V_4 – (10/4.42k) x 5.0 V

= (1+10/4.42k) x V_4 – 11.3 mV

and the output of op-amp B is:

V_B = (1+R7 / R5) x V_2 – (R7 / R5) x V_S(2)

= (1+10/4.42 k) x V_2 – (10/4.42 k) x 0 V

= (1+10/4.42 k) x V_2 – 0

The second stage of amplification connects these two outputs to a common differential amplifier (op-amp C) also shown in Figure 3. With some algebraic manipulation, the output voltage (V_{OUT}) of the entire amplification circuit is

V_C = (R12/R11) x [(1+R8/R6) x (V_2 - V_4) – (R8/R6) x V_S](3)

= (412K/1 k) x [(1+10/4.42 K) x (V_2 - V_4) – (10/4.42 K) * 5 V]

= (412) x [(1.002) x (V_2 - V_4) – 11.3 mV]

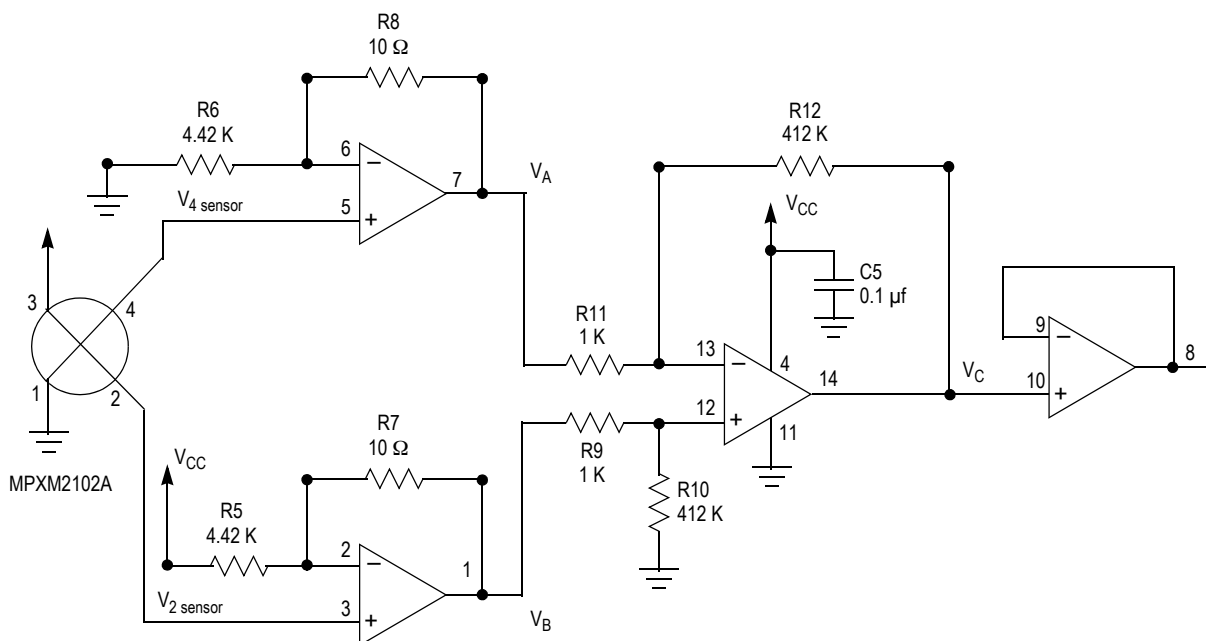= 412 x (V_2 - V_4) –11.3 mV

Figure 3. Amplification Scheme

The range of the A/D converter is 0 to 255 counts. However, the A/D values that the system can achieve are dependent on the maximum and minimum system output values:

Count = $(V_{OUT} - V_{RL}) / (V_{RH} - V_{RL})$ x 255(4)

where V_{Xdcr} = Transducer Output Voltage

V_{RH} = Maximum A/D voltage

V_{LH} = Minimum A/D voltage

Count (64 kPa) = (0.03 – 0.0) / (5.0 – 0.0) x 255 = 2

Count (105 kPa) = (4.85 – 0.0) / (5.0 – 0.0) x 255 = 247

Total # counts = 247 – 2 = 245 counts.

The resolution of the system is determined by the barometric pressure represented by each A/D count. As calculated above, the system has a span of 247 counts to represent a pressure from 64 kPa to 105 kPa. Therefore, the resolution is:

Resolution = (System Pressure Range) / Total # counts (5)

= (105 kPa — 64 kPa)/245 counts

= 0.17 kPa per A/D count

Microprocessor

To provide the signal processing for pressure values, a microprocessor is needed. The MCU chosen for this application is the MC68HC908QT4. This MCU is perfect for appliance applications due to its low cost, small eight-pin package, and other on-chip resources. The MC68HC908QT4 provide: a four-channel, eight-bit A/D, a 16-bit timer, a trimmable internal timer, and in-system FLASH programming.

The central processing unit is based on the high performance M68HC08 CPU core and it can address 64 Kbytes of memory space. The MC68HC908QT4 provides 4096 bytes of user FLASH and 128 bytes of random access memory (RAM) for ease of software development and maintenance. There are five bi-directional input/output lines and one input line that are shared with other pin features.

The MCU is available in eight-pin as well as 16-pin packages in both PDIP and SOIC. For this application, the eight-pin PDIP was selected. The eight-pin PDIP was chosen for a small package, eventually to be designed into applications as the eight-pin SOIC. If added circuitry for programming the microcontroller is added, a cyclone could be used to program an SOIC on the PCB. If your design requires software updates, consult the MC68HC908QT4 handbook for adding this option.

IMPROVEMENTS

The resolution of this design is limited by the eight-bit A/D converter on the microcontroller. Theoretically, the accuracy achieved by this device should produce an output when altitude change differs by about 41.54 feet (ΔZ). This occurs at approximately 1000 feet below sea level. Due to the logarithmic relationship between pressure and elevation, the accuracy of the results decreases as the device is elevated. At 12,000 feet above sea level, the device should recognize a change of about 65.53 feet (ΔZ) as shown in Table 3. A 10-bit, 12-bit or even a 16-bit A/D converter could be implemented in order to increase the resolution of this reference design.

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Table 2. Microcontroller Accuracy Comparisons

Z (ft)	P (kPa)	V (mV)	Amp scheme	Vamp (mV)	Vamp – 1 bit	P0	Px	ΔZ (m)	ΔZ (ft)	Micro
-1000	105	20.265	(Vx–12.8)*650	4852.3	4832.6	20.265	20.235	12.66	41.54	8 bits
12000	64.259	12.852		33.8	14.2	12.852	12.822	19.97	65.53	8 bits
-1000	105	20.265	(Vx–12.8)*650	4852.3	4847.4	20.265	20.257	3.15	10.35	10 bits
12000	64.259	12.852		33.8	28.9	12.852	12.844	4.97	16.32	10 bits
-1000	105	20.265	(Vx–12.8)*650	4852.3	4851	20.265	20.263	0.79	2.59	12 bits
12000	64.259	12.852		33.8	32.6	12.852	12.85	1.24	4.08	12 bits
-1000	105	20.265	(Vx–12.8)*650	4852.3	4852.2	20.265	20.265	0.05	0.16	16 bits
12000	64.259	12.852		33.8	33.7	12.852	12.852	0.08	0.25	16 bits

Table 2 shows the theoretical maximum resolution that this reference design can achieve. However, factors such as noise within the circuit, sensitivity of the sensor, and voltage offsets in the amplification scheme should be taken into consideration. Accommodating for these factors in the software can filter out some of these factors.

Further testing is required to determine the accuracy of the reference design without the limiting A/D converter.

DISPLAY

The display of the barometric pressure, barometric pressure history, current calculated altitude, and a simple weather prediction is displayed on a 16x2 LCD.
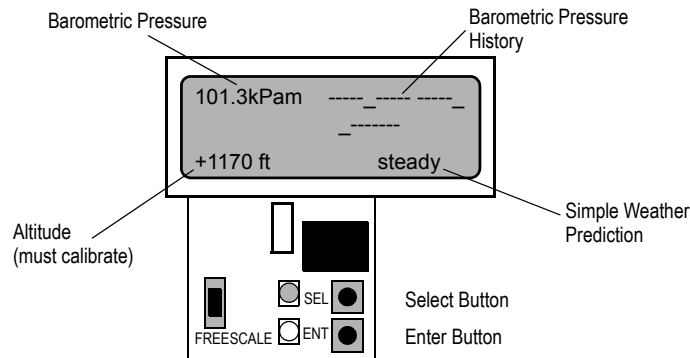

Figure 4. Barometric Display

Due to the limited number of bi-directional data pins on the microcontroller, a system was designed to serially buffer the display data. Using a shift register to hold display data, the LCD is driven with only three lines of output from the microcontroller: an enable line, a data line, and a clock signal while the two LEDs are multiplexed with the data line and clock signal.
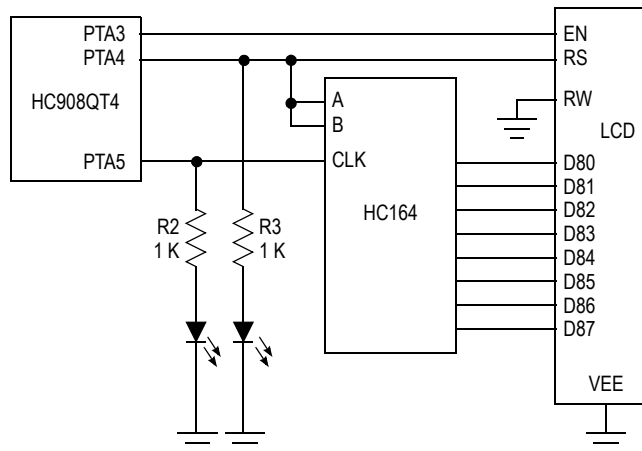

Figure 5. Multiplexed LCD Circuit

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Multiplexing of the microcontroller output pins allows communication of the LCD to be accomplished with three pins instead of eight or 11 I/O pins usually required. With an eight-bit shift register, we are able to manually clock in eight bits of data. The enable line, EN, is manually enabled when eight bytes have been shifted in, telling the LCD the data on the data bus is available to execute. The LCD will only be written to and the contrast can be held at a constant brightness, allowing the read/write and the VEE bits to be held low, also minimizing additional I/O lines.

Table 3. Parts List

Ref	Qty.	Description	Value	Vendor	Part No.
U3	1	Pressure Sensor	1.0	Freescale	MPXM2102A
C1	1	V_{CC} Cap	0.1 μF	Generic	
C2	1	Op-Amp Cap	0.1 μF	Generic	
C3	1	Shift Register Cap	0.1 μF	Generic	
D1	1	Red LED	—	Generic	
D2	1	Green LED	—	Generic	
S2, S3	1	Push buttons	—	Generic	
U1	1	Microcontroller	8-Pin	Freescale	MC68HC908QT4
U2	1	16x2 B&W LCD	16x2	Seiko	L168200J000
U4	1	Shift Register	—	Texas	74HC164
U5	1	Voltage Regulator	5.0 V	Fairchild	LM78L05ACH
U6	1	Quad Op-Amp	—	ADI	AD8544
R1, R4	1	1/4 W Resistor	10 K	Generic	
R2, R3	2	1/4 W Resistor	1.0 K	Generic	
R5, R6	2	1/4 W Resistor	3.65 K	Generic	
R7, R8	2	1/4 W Resistor	10 K	Generic	
R9, R11	2	1/4 W Resistor	1.0 K	Generic	
R10, R12	2	1/4 W Resistor	200 K	Generic	

OTHER

This system is designed to run on a 9.0 V battery. It contains a 5.0 V Regulator to provide a 5.0 V supply to the pressure sensor, microcontroller, and LCD. The battery is mounted on the back of the board using a space saving spring battery clip.

ALTIMETER/BAROMETER SOFTWARE

This application note describes the software version that was available during publication. However updated software versions may be available with further functionality and menu selections. Check our website update for updates to Sensor Products Reference designs.

Software User Instructions

When the system is turned on or reset, the microcontroller will flash the select LED and display the program title on the LCD for five seconds or until the select (SEL) button is pushed. Then the menu screen is displayed. Using the select (SEL) push button, the user can scroll through the menu options for a software program. To run the altimeter program, use the (SEL) select button to high-light the "Alti/Barometer" option, then press the enter (ENT) push button. The Altimeter program will display current barometric pressure reading, the calculated altitude in feet, a message displaying a simple weather prediction such as "sunny", "rainy", "steady" without a pressure change, and "history" before enough history is collected to make a prediction. In the top right corner of the display, a scrolling graphical history displays data points representing the past forty pressure readings.

Calibration and Calibration Software

There are two forms of calibration for this system. The first calibration is used for the barometer part of the system. This calibration was already done before you received the reference design and only needs to be done once per system. To calibrate the barometer module, a two-point calibration is performed using a highly accurate pressure generator. The system takes a calibration point at 64 kPa and another at 105 kPa. Holding down both the SEL and ENT buttons on system power-up will put the system into calibration mode. At this point, the calibration menu will be displayed with the previously sampled offset voltage. To recalibrate the system, apply a pressure of 64 kPa and press the SEL button (PB1). This A/D value is then saved to a location in the microcontroller memory. To obtain the second calibration point, using the accurate pressure generator apply a pressure of 105 kPa directly to the sensor. Then press the ENT button (PB2). This signal is similarly sampled, averaged and saved to

a location in FLASH. To exit the calibration mode, press the SEL (PB1) button.

The second calibration is done for the altimeter. The Altimeter requires a one-point calibration where a known altitude is entered with a known pressure. This ensures that changes in atmospheric pressure are due to increases or decreases in altitude and not changes in barometric pressure. By returning to the main menu, and selecting the "Set Elevation", the user can select an elevation by pressing the SEL button to cycle through the Elevation options from 0 to 12000 feet in 100-foot increments. Once the selection has been made the elevation is flashed into the microcontroller and the user is brought to the Altimeter/Barometer function. Calibration is required for each use of the altimeter module.
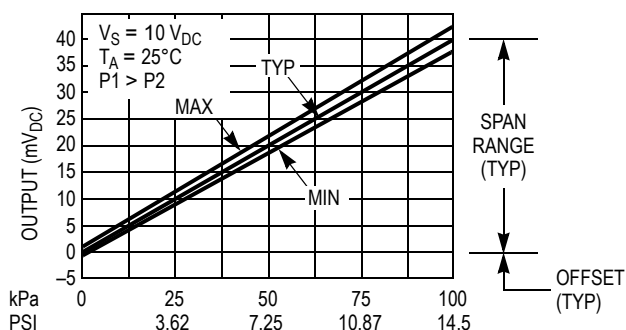

Figure 6. Analog Output to Pressure

CONVERTING ANALOG OUTPUT TO PRESSURE

Freescale pressure sensors have an extremely linear analog voltage output that is proportional to the pressure input. Since the sensor output is linear, the pressure can be calculated by using the equation of a line, $y = mx + b$, where y is the output voltage, the slope, m, is the Sensitivity, and the y intercept, b, is the Offset:

$$V_{OUT} = \text{Sensitivity} \times \text{Pressure} + \text{Offset}$$

With algebraic manipulation, pressure can be determined by:

$$\text{Pressure} = (V_{OUT} - \text{Offset})/\text{Sensitivity}$$

Below is an example of determining the pressure from the analog output of 9.5 mV using the Sensitivity and Offset of the MPX2102a sensor specified in the datasheet:

Pressure = $(V_{OUT} - \text{Offset})/\text{Sensitivity}$

= (9.5 mV – 0.5 mV) / 0.1 mV/kPa

= (9.0)/0.1 mV/kPa

= 90 kPa

where 0.5 mV is the typical offset for the MPX2102 and 0.1 mV/kPa is the sensitivity with a 5.0 V supply

This system uses additional amplifiers and an A/D converter that all add additional offset and gain errors; however, the translation function was corrected with the two-point calibration. The known pressure values that are used for calibration are the maximum and minimum pressures for the system, 105 kPa and 64 kPa respectively. The A/D values for

these known pressures are saved in the flash memory of the microcontroller.

$$\text{ATD} = (Po - P_{64kPa})/(P_{105kPa} - P_{64kPa}) \times 255$$

By algebraic manipulation, the following equation is reached to find the barometric pressure:

$$Po = (\text{ATD}/255) \times (P_{105kPa} - P_{64kPa}) + P_{64kPa}$$

Converting Pressure to Altitude

The method of determining altitude for this reference design is measuring the changes in barometric pressure. The relationship of pressure vs. altitude is not linear. As pressure decreases, altitude increases, but the higher the altitude gets the less pressure changes. The equation that was used for this reference design is:

$$P = (P0)\, e^{\wedge}[-(g/(RT)) \times (Z — Z0),$$

where P = pressure at an unknown altitude,

P0 = pressure at a known altitude,

e = a constant,

g = gravitational constant 9.8 (m/s^2),

R = dry air constant 287 J/(kg x K),

T = temperature at unknown elevation in Kelvin,

Z = unknown altitude in meters,

and Z0 = known altitude also in meters.

This equation originates from the hydrostatic equation:

$$dP = -\rho g dZ$$

in conjunction with the ideal gas law:

$$P = \rho RT$$

After some algebraic manipulation, plugging in constant values and converting meters to feet, the following equation was generated:

$$Z = Z0 — 27{,}887 \text{ in } (P/P0),$$

where Z = unknown altitude in feet,

Z0 = known altitude also in feet,

P = known pressure at unknown altitude,

and P0 = known pressure at known altitude.

For this system to calculate an altitude, Z, at a known pressure P, the user must enter a known pressure, P0, and its corresponding altitude, Z0. To accommodate for changes in barometric conditions, the known pressure and altitude data must be re-entered during each use to ensure accuracy.

Simple Weather Prediction

Atmospheric pressure at the Earth's surface is one of the measurements used to make weather predictions. Air in a high-pressure area compresses and warms as it descends. The warming air inhibits the formation of clouds. Therefore, the sky is normally sunny in high-pressure areas with a small chance of haze or fog. However, in an area of low atmospheric pressure, the air rises and cools. With enough humidity in the

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air, the rising air will cool, the air will condense forming clouds and precipitation in the form of rain or snow.

This reference design saves the current pressure reading and compares it to past pressure measurements. It determines if there was a pressure drop or a pressure increase. Using this information, it makes a simple weather prediction by sending a message of 'sunny' for a pressure increase, 'rainy for a pressure drop, and 'steady' for no significant change in pressure.[1]

CONCLUSION

The Altimeter is one of many applications for the MPXM2102AS pressure sensor. This reference design can be used as a reference for developing more integrated barometer applications such as hand-held weather stations, altimeter features for camera or GPS systems, as well as barometric pressure monitoring systems for industrial systems. The MPXM2102AS is an excellent pressure sensor for this application since it is calibrated and temperature compensated. By having these features available on-chip, there is a large savings in PCB real estate in addition to savings in cost for external components

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Table 4. Elevation Pressure and Temperature Changes

Altitude Above Sea Level		Temperature		Barometer	Atmospheric Pressure	
Feet	Meters	F	C	mm * Hg	psi	kPa
-1000	-305	63	17	787.9	15.23	105.0
-500	-153	61	16	773.9	14.96	103.1
0	0	59	15	760.0	14.69	101.33
500	153	57	14	746.3	14.43	99.49
1000	305	55	13	733.0	14.16	97.63
1500	458	54	12	719.6	13.91	95.91
2000	610	52	11	706.6	13.66	94.19
2500	763	50	10	693.9	13.41	92.46
3000	915	48	9	681.2	13.17	90.81
3500	1068	47	8	668.8	12.93	89.15
4000	1220	45	7	656.3	12.69	87.49
4500	1373	43	6	644.4	12.46	85.91
5000	1526	41	5	632.5	12.23	84.33
6000	1831	38	3	609.3	11.78	81.22
7000	2136	34	1	586.7	11.34	78.19
9000	2441	31	-1	564.6	10.91	75.22
9000	2746	27	-3	543.3	10.5	72.40
10,000	3050	23	-5	522.7	10.1	69.64
15,000	4577	6	-14	429.0	8.29	57.16

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1. This information was found from the USA Today Weather Book from USAToday.com.

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```
                                    Start
                          A/D converter is set up and enabled
                             and variables initialized

                                       │
                                       ▼
PB1 and PB2                  ┌──────────────────┐
  pressed                    │  Start in Calibration │
◄────────────────────────────│       Mode?          │
                             └──────────────────┘
                                       │  PB1 and PB2 not
        │                              │   pressed
        ▼                              ▼
┌──────────────────┐         ┌──────────────────┐
│ Display Calibration │        │  Display Welcome  │◄──────┐
│     Message        │        │     Message       │        │
└──────────────────┘         └──────────────────┘        │
        │                              │                   │
        ▼                              ▼                   │
┌──────────────────┐         ┌──────────────────┐          │
│ Apply 64 kPa Pressure │     │  Display Altitude or │        │
│ Average 256 Readings │      │   Set Elevation?     │        │
└──────────────────┘         └──────────────────┘          │
        │                              │
        ▼                              │   PB1 pressed
┌──────────────────┐                   │
│ Apply 105 kPa Pressure │             │
│ Average 256 Readings │───────────────┘
└──────────────────┘
```

| | "Select Elevation" Menu Displayed | Cycle through 0 to 12000ft selections |

Read 256 A/D values
Average 256

Convert digital reading
to history graph

Convert A/D Values
to Pressure (kPa)

Calculate Altitude
in Feet

Display Barometric
Pressure, Altitude and
History

Figure 7. Altimeter/Barometer Software Flow Diagram

REFERENCES

Williams, Jack. (2001). Understanding Air Pressure. *The Weather Book*, 5, 117–123. Retrieved April 4, 2003, from http://www.usatoday.com/weather/wfront.htm

NOTES

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