International Global Navigation Satellite Systems Society
IGNSS Symposium 2013

Outrigger Gold Coast, Australia
16-18 July, 2013

Using Barometers to Determine the Height for Indoor Positioning

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ABSTRACT

It is well known that atmospheric pressure decreases when altitude increases. Models have been created to relate altitude or height to pressure. A barometer can measure the air pressure and then the altitude can be calculated. Before the era of GNSS, barometers were widely used to determine heights outdoors. The invention of GNSS was a revolution in positioning and navigation. However, it does not work in an indoor environment. Alternative technologies have been developed such as Wi-Fi fingerprinting mainly for 2D positioning and navigation. In some of the applications, 3D or 2.5D (the level of the building) is required. Using barometers is a possible solution and some new mobile phones have a built in pressure sensor. But there are many issues that should be considered. Is height determined from barometric pressure accurate enough? Is there a latency problem? Does the air conditioning in an almost sealed building significantly affect height readings? This paper discusses the necessary considerations to use barometers for indoor applications based on experiments. Possible solutions are suggested.

KEYWORDS: Barometer; Indoor positioning; Altitude

1. INTRODUCTION

We have heard many times that barometers can be used to determine the altitude for indoor positioning [1][2]. An often used example is that when you park your car in the multi-floor car park, you can use your phone to log the car's location – X Y coordinate and height using indoor positioning technologies. Then after your shopping the mobile phone can navigate you back to where the car is parked. There are many technologies that have been developed to give your X and Y coordinates, but how to decide the height? “Use barometer” – is often the answer. It has been observed that atmospheric pressure decreases when the altitude increases. Models have been created to relate height to pressure. A barometer can measure the air pressure and then the altitude can be calculated. This looks like a very straight forward application. Is it that simple?

In the past barometric heights were used outdoors. To determine heights outdoors now we have GNSS instead of barometric levelling. For reconnaissance planning, to plot profiles and for design purposes we have global Digital Elevation Models (DEM) that are freely available. But these don’t work indoors. To decide which floor or building level you are on probably requires height measurements accurate to better than 3m. Vanicek and Krakiwsky [3] state “When the proper measuring technique is used, the typical accuracy of barometric heighting is about σ = 2m in both flat and rolling terrain. In mountainous terrain … the accuracy deteriorates…” Other than accuracy, there are many other issues that should be considered carefully. For instance is there a latency problem? Does the air conditioning in an almost sealed building significantly affect height readings? Is a reference station required?

This paper discusses the necessary considerations to use barometers for indoor applications based on experiments. A review of atmospheric pressure is given in the following section and then some tests of barometers/altimeters are reported in Section 3. In Section 4 two methods for indoor height determination based on air pressure are discussed. Finally, concluding remarks are given.

2. REVIEW OF ATMOSPHERIC PRESSURE OUTDOORS

As we all know by observing the weather, the atmosphere is not always the same. One of its parameters is pressure. The atmospheric pressure is the weight exerted by the overhead atmosphere on a unit area of surface. Barometers are used to measure air pressure. Air pressure and the amount of water in the air also change with time, location and height [4]. The International System of Units (SI) for pressure is the pascal (Pa), but the unit of pressure generally used for the atmosphere is the hPa or millibar (mb).

$1hPa \equiv 1mb \equiv 100Pa$

In this paper all values involving pressure are based on hPa (or mb), unless otherwise stated.

2.1 Barometers

The mercury barometer was developed in the 1600s and soon after led to the realisation of the relationship between altitude and height. There are many types of barometers ranging in size from large wall mounted glass tubes filled with mercury which are impractical for field use, to brick size diode based barometers, to simple analogue pocket size aneroid (without fluid) barometers with dials, and digital electronic barometers the size of calculators, and finally to small electronic circuits inside some GPS, sports watches and smart phones [6-8]. Size and ease of use has improved over the years but perhaps not the accuracy. However the accuracy of a barometer might already be good enough if the errors in it are smaller than the spatial and time variations in the atmosphere’s pressure and the applicability of the formula that converts pressure to height.

Meteorologists, pilots and others use barometers or altimeters, but so have surveyors for many years. In the early days of VLBI (Very-long-baseline interferometry) and GPS we also used air pressure measurements to correct for tropospheric delay to signals. Before the introduction of Electronic Distance Measurement (EDM) and GPS some surveyors used barometers and altimeters for height measurements [5].

2.2 Pressure and Height

It has been observed that atmospheric (or air) pressure gets lower as you climb, as does temperature. Models of the typical values of the atmospheric parameters such as temperature and pressure have been produced over the years. For example the International Civil Aviation Organization has produced a 'Standard Atmosphere'. The values of pressure at varies heights above sea level in the ICAO model can be graphed here (see Fig. 1). The actual values at various heights for this model can be found in [9]. These models of the atmosphere are based on observations outdoors where sun and wind affect conditions; they don't necessarily represent air in man-made conditions such as underground mines and very tall air conditioned buildings.

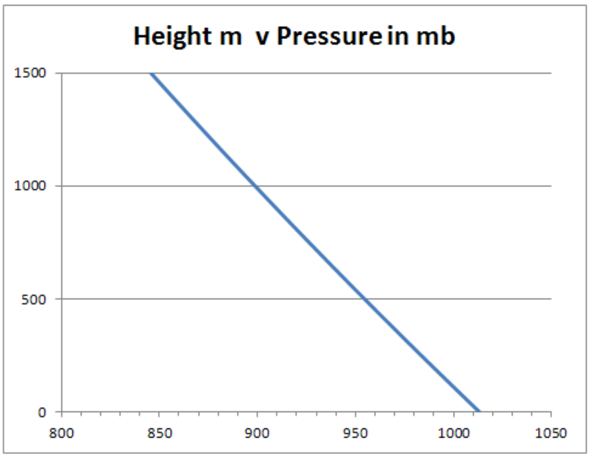

Figure 1. Pressure vs. height

According to this model pressure drops by about 0.11hPa for every 1m increase in height. Alternatively height changes by about 8.7m for every 1hPa change in air pressure.

The barometric law [10] relates atmospheric pressure p to altitude H as:

$$P = P_0 e^{-\frac{Mg}{RT}H} \qquad (1)$$

where P_0 is pressure at Mean Sea Level (MSL), M is the molecular weight of air, g is the gravitational constant, R is the universal gas constant, and T is the temperature in Kelvin. There are simplified formulas to decide the height based on pressure such as [11]:

$$H = C1(1 - (P/P_0)^{C2}) \qquad (2)$$

where C1 and C2 are constants which depend on temperature its rate of change with height and other matters. The values for these terms depend on which model is chosen. Typical values are P_0 = 1013.25 hPa, C1 =145367.59, and C2 = 0.19023.

The process appears quite straight forward. If we measure air pressure or changes in air pressure we can calculate our height above sea level, or changes in our height. If we could measure pressure to 0.1hPa accuracy then we could determine heights to about 1m accuracy. But it is not that simple. The actual atmosphere at the time of measurements may not exactly match this model or any one of the other models that have been produced. A further complication is that the atmosphere changes during the period of navigation or positioning.

The earth's atmosphere is comprised of layers of air with varying densities. A surface of equal pressure is known as an isobaric surface. When points of interest have a lateral separation the isobaric surface is often assumed to be a plane parallel to the datum plane. In reality the isobaric surface can be tilted, buckled and in most cases very irregular. This is generally caused by the local weather conditions and topography. Field techniques can be employed to determine the tilt of the surface if pressure readings are taken at three or more points of known elevation.

Barometers are normally calibrated to a standard atmosphere which assumes a temperature and pressure of the air column at mean sea level (usually 15°C and 1013.2mb). A 'standard atmosphere' also assumes the air is dry and of the same composition at all altitudes and the value of gravity is uniform.

Changes in the atmosphere are generally regular and dependent on season, altitude and local weather conditions. Non periodic changes in pressure are mainly caused by frontal conditions, unstable air masses and irregularly developing pressure systems. Topography will affect the pressure as the shape of the earth controls the intensity of the wind and the air temperature. When a side of the earth or of a building faces the sun it is heated which causes the atmosphere to be heated leading to a rise in the atmosphere's temperature and hence a drop in pressure. Generally the windward side of a hill will have a higher pressure than the leeward side. The pressure in a valley can be changeable, depending if they are protected from the wind or if there is turbulent airflow. So we expect forced air ventilation conditions indoors and underground may affect the reliability of determine height from pressure measurements.

2.3 Altimeter

A barometric altimeter is an instrument that measures air pressure and displays the altitude (height) of an object. The conversion from pressure to height involves a nonlinear calibration using an equation derived from equation (1), e.g.:

$$H = cT \ln \frac{P_0}{P} \tag{3}$$

where c is a constant.

However, outdoor readings of height (altitude) from a pressure based altimeter can vary by tens of metres owing to a sudden change in air pressure, such as from a cold front, or a gradual diurnal change without any actual change in altitude/height of the instrument.

When the air is stable a barometric altimeter, can be more reliable, and often more accurate, than a navigational GPS receiver for measuring relative height of two or more points. Consequently, some navigational GPS receivers have inbuilt altimeters and algorithms to combine the GPS and pressure data to produce the displayed height. But because barometric pressure changes with the weather, users should periodically recalibrate, or at least check, their altimeters when they reach a point with a known height. Figure 2 shows results of an outdoor test using a barometer/altimeter and a differential GPS. The altimeter was calibrated by entering known height of a start point.

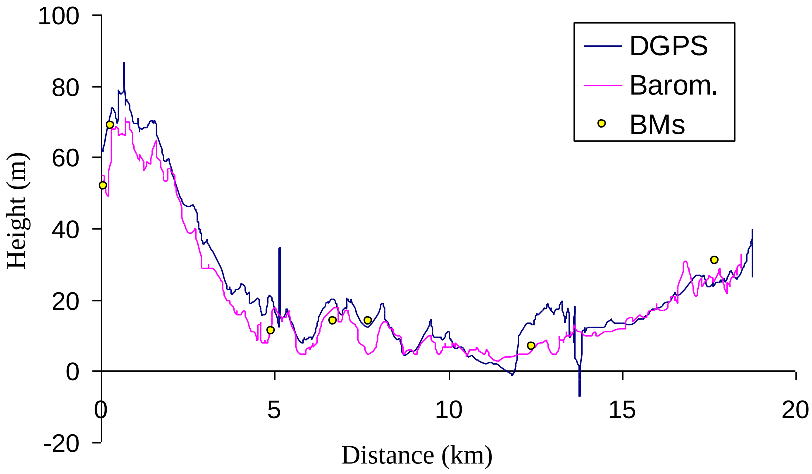

Figure 2. A surveyed route using differential GPS and altimeter.

Before EDM and GPS existed, surveyors developed methods to use barometric leveling (or heighting) to establish low-order height control. There are various field techniques used when establishing barometric heights [11]. Barometric observations will not give an accurate absolute height (i.e. above mean sea level) but they can produce reliable values of the difference in height between points or relative to a single point in an area of similar atmosphere. We will see later in this paper, the same concept applies indoors.

3. TESTS OF BAROMETERS

Several tests were carried out (mainly for indoor environments) to investigate the methods that could be used for indoor height determination. The instruments used in these tests are shown in Fig. 3.

Figure 3. Instruments used in tests (from left to right: AIR Barometer/Altimeter (AIR-HB-1A), Polar watch (model s710i), Samsung Galaxy Nexus S and Samsung Galaxy S4)

3.1 Latency

Latency is a measure of time delay experienced in a system. If there is a significant delay for a barometer to report the air pressure, we may get a wrong altitude, for instance when we go up in a quick lift. When an AIR Barometer/Altimeter was tested, a latency of several seconds was observed. When the researcher changed the floor level using stairways, it took a while for the altimeter to catch up – its reading was changing for a while then stabilized. When the mobile phone was tested, it was found that the latency was much less significant. A researcher carrying a smart phone took a lift from Level 4 to lower ground level and then back to level 4. The air pressure measurements and linear accelerations were logged. The linear acceleration sensor provides a three-dimensional vector representing acceleration along each device axis, excluding gravity. The output rate of acceleration is 100Hz while that of air pressure is 5Hz which is much higher than that of the AIR Barometer/Altimeter. Fig. 4 displays the air pressure and the acceleration in Z axis. The change of the acceleration indicated the change of the status of the lift. At the beginning, the lift was static; the first pair of bumps shows the lift moved down and then stopped. The lift stayed at Level lower ground for a few seconds, and then moved back to Level 4 (indicated by the second pair of bumps). It shows that the latency of the air pressure measurement can almost be neglected. It can also be found that with the change of one floor, the air pressure changes for about 0.42hPa which is significantly larger than the measurement noise (about 0.2hPa for Samsung Galaxy Nexus S built in pressure sensor BMP180).

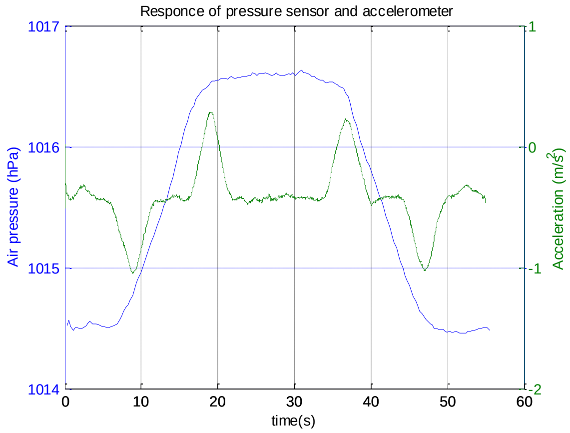

Figure 4. The response of pressure sensor and Z axis accelerometer when the lift moved down and then up.

3.2 Daily Variation

A test was carried out using a smart phone to log the air pressure for over 60 hours. The phone was placed in a typical office room without air conditioning. A 12 hour circle can be found – with maximum values at midnight and noon and minimum value at 6am and 6pm (refer to Fig. 4). The cycle does not repeat exactly, the maximum or minimum values can vary by up to 2hPa within a few days. Several days later, the same test was repeated, the periodic phenomenon was also found, however, the peaks and valleys were shifted.

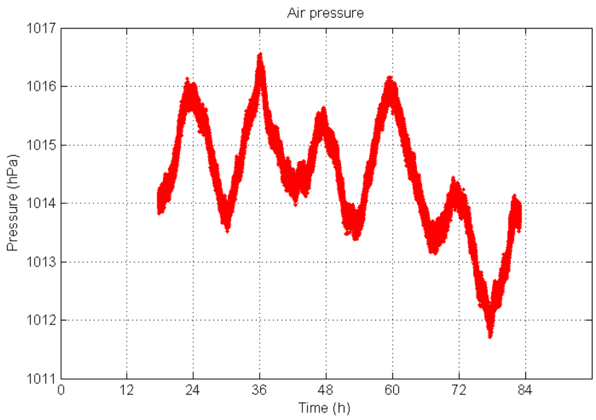

Figure 4. Daily variability of air pressure

3.3 Measurement Differences Between Instruments

Three barometers/altimeters (two AIR Barometers/Altimeters and one Polar watch) were tested at a survey control point. Air pressure values and height reported were recorded at different times during a day. Fig. 4 depicts the air pressure measurements and the heights. Since the watch did not report air pressure, on the left plot only two lines were displayed. There are clear constant offsets between the pressure measurements (0.6hPa) and reported heights (5.3m between the green line and red line and 21.6m between blue line and red line).

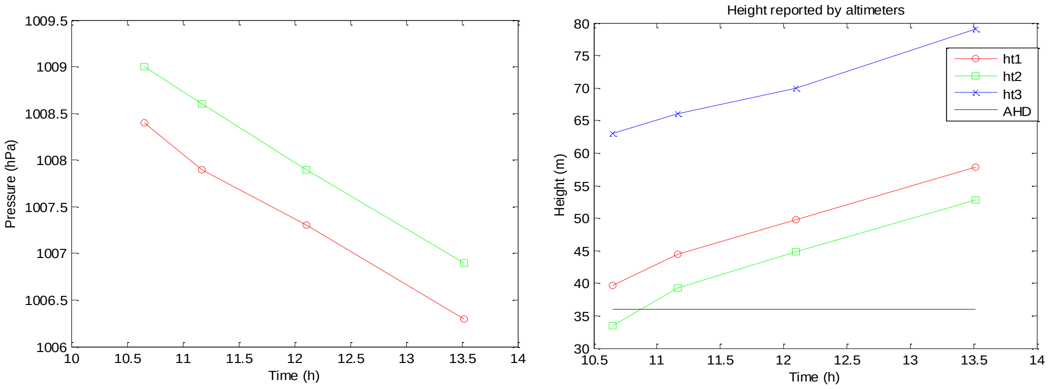

Figure 5. The pressure measurements of two barometers (AIR Barometer/Altimeter) (left) and the heights (right) reported by altimeters (2 AIR Barometer/Altimeter and a Polar watch) at the same location but different times during a day. On the right plot, the black line gives the true height (Australian Height Datum), and the blue line is the height reported by the watch.

Two smart phones were also tested over a day. The built-in air pressure sensors are all reported from Bosch (BMP180 for Galaxy Nexus S, the model for Galaxy S4 is not clear). Fig. 6 compares the air pressure measurements from the two phones. Again, the air pressure varies and there is an offset between the two sets of measurements. It appears that the offset is constant; however further investigation shows that the offset varies as well (between 2.1hPa and 2.5hPa, after applying smoothing). It can also be found that the measurement quality of Galaxy S4 is better as the noise is smaller and the outliers are not observed. Further investigation shows that many measurements from Galaxy Nexus S were missing because the software to record the data has filtered out many outliers.

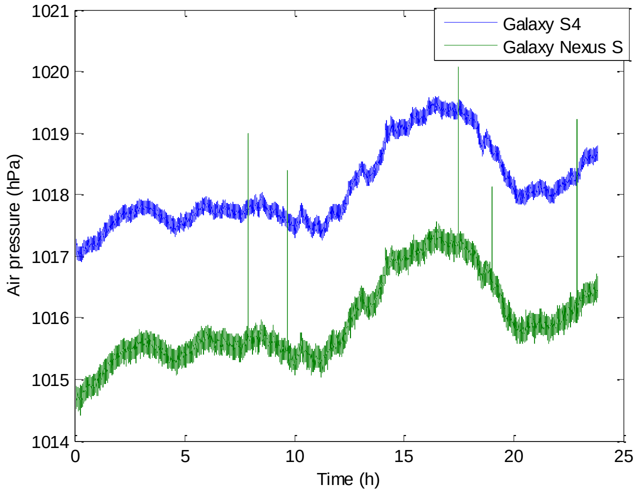

Figure 6. Comparison of air pressure measurements from two smart phones.

3.4 Stability in Short Term

Air pressure varies over time, however, over a short period of time it is relatively stable. The length of the period depends on the variation of the local atmosphere. For instance, during the test, most of the time the AIR Barometer/Altimeter reported changes less than 0.1hPa every 10 minutes. For smart phones, within a few minutes, the variation is not larger than 0.2hPa which is equivalent of 1-2 meters. The typical difference of floor heights of a building is 3.5 meters. So it is safe to use barometer to locate a user within a short period of time without recalibration.

3.5 Using a Reference Station

There are many places around the world that report air pressure in real time or near real time. There is a possibility to use these stations as a reference (as the height of the station is known) to correct the air pressure reported by mobile devices. A test was conducted in an office building. Air pressure, humidity and temperature were measured and logged every 10 minutes. Weather observations from an airport station were downloaded later. The airport is about 5km away from the building used for testing. Fig. 7 compares the measurements at these two places. It can be seen that the two sets of air pressures have clear correlation, an almost constant offset between the two pressures can be observed. As expected, the temperature and humidity in an indoor environment are more stable than those in an outdoor environment.

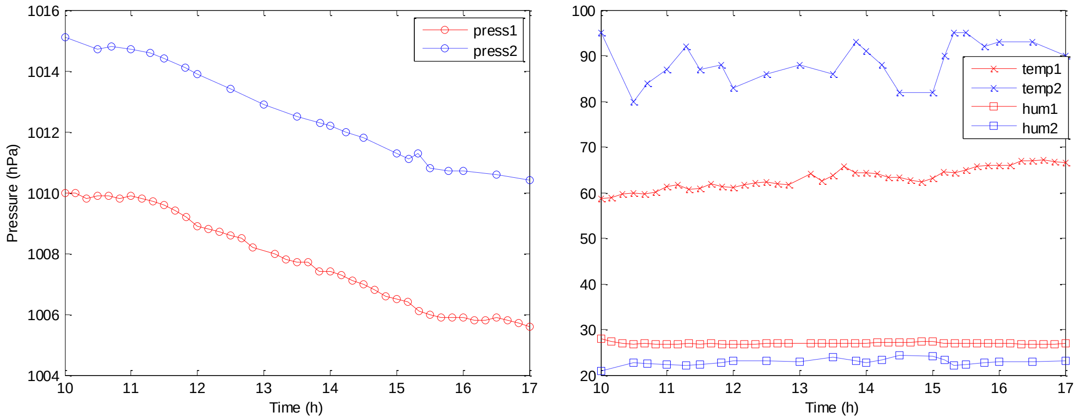

Figure 7. Comparison of air pressure (left), temperature and humidity (right) at airport station and at an office

3.6 Library Tower Test

In this test, two AIR Barometers/Altimeters and one Polar watch were used to measure the air pressure and height in a high rise almost sealed air conditioned building – the UNSW Library tower. The test lasted 26 minutes; air pressure measurements and reported heights at different levels were recorded. Results are shown in Fig. 8. Constant offsets can be seen between measurements of different instruments at different levels or at the same level but different time. Air pressure was measured twice at Level 1 and Level 10 at different times (17 minutes and 9 minutes intervals respectively). Clearly, compared with the ground truth (which were independently surveyed by a theodolite/EDM total station), there is an initial offset and a drift. After allowing for offset and drift the altimeter derived heights of the various levels in the air conditioned library tower the maximum error was 2.8m and usually less than 2m.

However without post processing the data for offset and drift the accuracies of relative heighting do deteriorate with the time between start and return of a "shopping – car park" trip. In this experiment the initial offsets could be tens of metres and the heights drifted by about 6m per hour. For relative positioning, large offsets are eliminated but drifts of heights do need to be considered for long "shopping" trips.

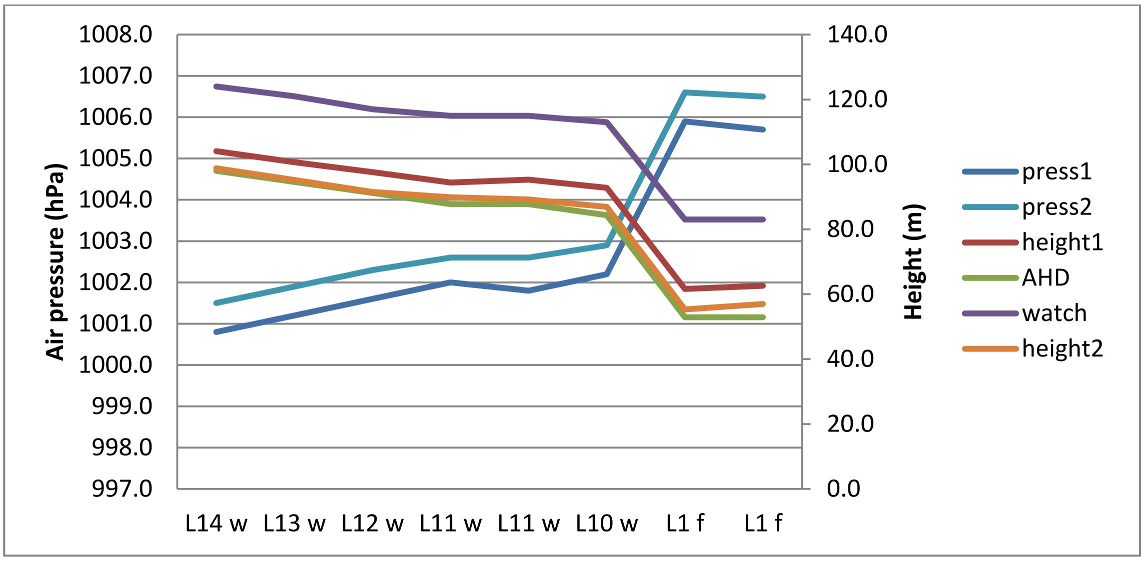

Figure 8. Test results of the Library tower test. The x axis gives the locations that the measurements occurred, L means floor level.

4. POSSIBLE SOLUTIONS

Based on the experiments discussed above, it is impossible to accurately determine a height using barometer/altimeter in indoor environment in an absolute manner. However the survey techniques of using air pressure for outdoor relative height determination can be applied, i.e. *barometric observations can produce reliable values of the difference in height between points or relative to a single point in an area of similar atmosphere*. Please note a *similar atmosphere* is required. Hence the area cannot be too large and a reference (or a reference station) is needed. An intuitive solution is initializing the barometer before using it for positioning and reinitializing it before the drift of the measurements goes too large.

4.1 Determine Heights Using Reference Stations

This method requires at least one reference station.

1. Measure the air pressure P_{U0} using a smart phone at a place with known height (H_{U0}) and obtain the reference station pressure P_R (assume the real time data is available).
2. At a 'rover' location that requires height, measure the air pressure P_U and obtain the current reference station air pressure P_R
3. Compute $\Delta P_R = P_R' - P_R$ and $P_{U0}' = P_{U0} + \Delta P_R$
4. Estimate ΔH_U using the following equation which is derived from equation (3):

$$\Delta H_U = -cT \ln \frac{P_U}{P'_{U0}} \tag{4}$$

where c is a constant value, T is the only value unknown. Fortunately, there are many ways to obtain the temperature and the height is not very sensitive to it (293.15K can be assumed).

5. Compute $H_U=H_{U0}+\Delta H_U$

If H_{U0} is unknown, the absolute height cannot be computed; however the relative height can still be obtained. In many applications, users do not care the absolute height. For instance, if 15 minutes ago you were in level 4, and now you find the height has been changed for about -7m, you know you are in level 2 (if the difference between floor heights is 3.5m), that is 2 floors below the previous location. The reference station should not be too far away from the indoor environment of interest as a *similar atmosphere* is required. It can be seen in equation (4) that the air pressure at the reference station is not required if ΔP_R is 0 or very small which typically means the interval of the two measurements is small (say a few minutes). Hence using barometers to detect the change of floor level is a valid application.

4.2 Determine the Height Using a Single Barometer

A reference station is not commonly available currently, but it is possible to use other positioning technology to estimate the height. For instance, Wi-Fi positioning technology can provide the level estimation if the smart phone can reliably receive signals from access points installed at a curtain floor. This leads to a solution without a reference station (using Wi-Fi as an example), of course some basic information about the indoor environment such as the difference between floor heights, is needed

1. Use Wi-Fi position technology to obtain 2.5D position (x, y and floor level).
2. Measure the air pressure and use equation follows to estimate the air pressure at other floor levels:

   $$P_2 = P_1 e^{-\frac{\Delta H}{cT}} \tag{5}$$

   And a threshold can be set to detect the change of floor level.

3. Repeat 1 and 2 periodically
4. When the user change floors (using lift or stairway), Wi-Fi positioning result is normally unreliable (signals from access points at different floors can be received at the same time), especially the height. If the variation of the air pressure reaches the threshold, report that the user moves to a new floor level.
5. At the new floor level, once Wi-Fi positioning result is reliable, repeat steps 1 and 2.

In this way, a barometer can be used to estimate the height reliably without a reference station.

4.3 Testing of the Proposed Methods

A test to apply the methods discussed above was carried out in a multilevel 'windowed' office building. The air pressure on each floor level was measured at 10 am and 12 noon using a smart phone (see Table 1, columns 2 and 3). The reference station was located at an airport 5km away (the data can be found online [12]). We measured the air pressure at level 4 and we knew the current floor level through Wi-Fi positioning. Then we applied method 4.2 (single barometer) with the knowledge of the difference of floor heights. The air pressure on other levels can be computed and are listed in column 4. It can be seen that the estimated values are very close to the measured values with maximum 0.1hPa error. If we move down the building from Level 4, the smart phone can measure the air pressure and compare the current pressure with the estimated pressures on other levels. Hence our current floor level can be decided. If at Level 4, we also collected the reference air pressure, then method 4.1 can be applied. The change of air pressure was significant in the 2 hours; 2.4hPa which can introduce about 20m error in height. After applying the corrections, at 12 noon, the relative height on other levels can be accurately estimated (see the last column in Table 1). Again, the results can correctly locate our current floor level.

TABLE I. TESTING RESULTS OF APPLYING THE TWO PROPOSED METHODS

	10:00am (measured P)	12:00noon (measured P)	Single Barometer (estimated pressure)		Two Barometers (estimated ΔH at noon, m)
Airport (5km away)	*1016.0/13.1°C*	*1013.6/16.0°C*			
Level 4	*1009.4*	*1006.9*	-	-	0.8
Level 3 (-3.5m)	1009.8	1007.3	1009.8	1007.3	-2.5
Level 2 (-7.0m)	1010.2	1007.8	1010.2	1007.7	-6.7
Level 1 (-10.5m)	1010.6	1008.1	1010.7	1008.1	-9.2
Level G (-13.5m)	1011.1	1008.6	1011.1	1008.6	-13.4
Level LG (-17.0m)	1011.5	1009.0	1011.5	1009.0	-16.8

5. CONCLUDING REMARKS

The questions raised at the beginning of this paper were whether mobile phones or similar devices that have a built in pressure sensor can determine heights indoors accurately enough for positioning and navigation; is there a latency problem; and does air conditioning in a sealed building significantly affect height readings. After applying the methods discussed in this paper, we conclude that we can use such barometers to find which floor level your car is parked on in a multi-floor car park, *relative height can be accurately estimated.* However, some requirements must be met.

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