Calibration of Smartphones
for the use in indoor navigation

Friedrich Keller, Thomas Willemsen, Harald Sternberg
Dept. Geomatics, HafenCity University
Hamburg, Germany
friedrich.keller@hcu-hamburg.de, thomas.willemsen@hcu-hamburg.de, harald.sternberg@hcu-hamburg.de

***Abstract*— The HafenCity University has been working for quite some time with the possibilities for indoor positioning with the focus on the use of current smartphones. Latest smartphones, as in this paper the Samsung Galaxy Nexus, include necessary sensors for relative positioning. These sensors will be analyzed before implementing an indoor navigation by using a smartphone. Hereinafter the gyroscope and the barometer are investigated. An approach for the calibration of the gyroscopes using a total station as well as a view on the possibility of storey detection via air pressure measurements will be shown in the following.**

Keywords; Indoornavigation, Gyroscope, Barometer, calibration

I. INTRODUCTION

Currently professionals are working on the best solutions for indoor navigation worldwide. Applications should be made available as user-friendly and easily as possible to a wide audience. Until a few years ago many individual sensors and a complex technology were needed for indoor navigation. Nowadays, smartphones and tablets are quite capable of providing all the information needed for indoor navigation. Interim developments which realize MEMS-sensor-boards (MicroElectroMechanical Systems) without operating systems like Android and iOS, should not be neglected, because it's possible to operate with the actual raw data. The mobile phone operating systems have always a last ambiguity about the internal processing. It is a requirement for the reliable feasibility of an indoor navigation with a smartphone that the performance of the sensors is known. In this paper a closer look at the sensors of the Galaxy Nexus is taken.

II. SMARTPHONE SELECTION

The smartphone market is a very fast-moving business which is driven by the major manufacturers Samsung (20.7% market share in Q1_2012 [3]), Nokia (19.8%) and Apple (7.9%). Above all, Samsung and Apple are generating new innovations and products. On 19 October 2011 the Samsung Galaxy Nexus (*Ice Cream Sandwich*) with Android 4.0 was presented in Hong Kong to the public. Figure 1. shows the smartphone and its reference coordinate system of the internal sensors.

Figure 1. Samsung Galaxy Nexus
(http://developer.android.com/reference/android/hardware/SensorEvent.html)

The device is developed in a partnership between Google and Samsung. The phone and operating system were developed collaboratively by engineers from both companies. It is the third generation successor to Google's flagship phones. The processor is a OMAP4460 from Texas Instruments. The chip has a dual-core CPU operating up to 1.5 GHz. The smartphone is controlled by the operating system, Android 4.0. The Android operating system had in the first quarter of 2012 a market share of about 56.1%, followed by iOS with 22.6% [6].

From the authors' point of view the Android operating system is preferable. As compared to iOS, the Android is a free software, which is developed as open source. However, Apple's iOS centralized process of the publishing of apps as well as a possible censorship and secrecy agreements are inhibit to any innovation. Another important aspect for the choose of the Galaxy Nexus are the built-in sensors. The sensors are shown at a glance in Table I. The smartphone has all the necessary sensors for indoor navigation in MEMS structure.

At this point the manufacturer's specified accuracies of the sensors is listed. Due to the different information in the data sheets, a direct classification of the sensors in an accuracy class is difficult. Among other things, there is information about the resolution, the accuracy and noise.

TABLE I. GALAXY NEXUS SENSORS[4]

	Name	***Hersteller***
Triaxial Gyroscope	MPU3050	InvenSense

978-1-4673-1954-6/12/$31.00

	Name	***Hersteller***
Triaxial accelerometer	BMA250	Bosch
Barometric pressure	BMP180	Bosch
Triaxial Geomagnetic	YAS530	Yamaha
Bluetooth, GPS, WiFi, Camera		

The programmable full-scale range given by the sensor manufacturer InvenSense for the gyroscope is ± 250 °/sec, ± 500 °/sec, ± 1000 °/sec, ± 2000 °/sec. This corresponds with 16 bits to a resolution of 0.004 °/sec to 0.03 °/sec. The cross-axis sensitivity is specified at 2% and the non-linearity of 0.2%. The noise is specified at 0.1 ° / sec. InvenSense indicates that the sensitivity of the sensors are calibrated with 1% before leaving the factory. TABLE II presents as a direct comparison the market conditions MEMS-gyro-sensors. It is noticeable that the sensors have large significant differences in sampling frequency, resolution, noise and price. The sensors cannot be set easily in relationship and it is to emphasize again the difficulty to classify such sensors.

TABLE II. MEMS-GYROS COMPARISON [8]

Sensor	***Max. sampling rate (Hz)***	***Sensitivity (500 dps(°/sec))***	***Noise [dps/sqrt(Hz)]***	***Price [€]***
MPU-60x0	8000	15.28	0.005	4.00
MPU-3050	**8000**	**15.28**	**0.01**	**9.20**
LSM330DL	760	17.50	0.03	7.35
L3G4200D	800	17.50	0.03	12.95
ITG-3200	8000	15(guess)	0.03	7.60
L3GD20	760	17.50	0.03	7.05

The accelerometer is, like the gyroscopes programmable to different operation ranges. The range from ± 2g to ± 16g is available. If ± 2g is selected the resolutions is 3.91mg and with ± 16g it is 31.25mg. The Zero-g offset is ± 80 mg according to the datasheet.

The barometer is from Bosch with a working range of 300 - 1100 hPa indicated. For the typical operating range between 950-1050 hPa at 25 ° C, a relative accuracy of ± 0.12 hPa (equivalent to ± 1 m) are specified. For the entire operating range, Bosch specified an absolute accuracy of the pressure of - 4.0 hPa to + 2 hPa and for the integrated temperature sensing of ± 1 °C. Just this barometer is different between the Galaxy Nexus and all other smartphones, at this time in the smartphone market. It is one of the first smartphones which has built in a barometer. Another device in which a barometer was installed is the MOTOROLA XOOM. According to Samsung, the barometer is used in the device, similar to the assisted-GPS, to allow a quick fix of the GPS solution. The barometer is used to support the height [5].

The three-axis magnetometer, developed by Yamaha, has a working range of ± 800 micro-Tesla (µT). It has a resolution of 0.15µT (X, Y), 0.3µT (Z) with a measurement frequency of 1.5msec.

Crucial to the choice is the number of sensors in the Galaxy Nexus and the Android operating system. Only a responsive sensor for temperature measurement is missing.

All the above data are taken from the respective manufacturers' data sheets, where you can find more detailed information.

III. SENSOR EXAMINATION

In this paper we discuss in more detail two of the implement sensors. Firstly, the gyroscope is considered in more detail and a possible way for calibration is demonstrated. Second, the barometer is investigated as a new sensor in smartphones.

A. Gyroscope

For the investigation of multi-axis gyroscopes typically accurate rotary tables are used. These rotary tables cost to purchase, depending on equipment, far more than 480,000 €. Here will now be shown that for studies of MEMS gyros total stations can be used. The use of total stations is not new, in [10] they are used for the calibration of MEMS accelerometers.

1) Scale determined by tilting

[9] describes that by simply tilting the sensor about 90 degrees, a scale factor of the gyros can be determined. The rotation speed can be detected by a uniform turning about an axis in a relatively short time. The angle can be derived by integration of the rotation speed and can be compared with the correct angle. This method can be implemented using a programmable total station. In this project, it was a Leica TCRP1105+ Total Station. The advantage of Leica total stations is that they can be programmed by using the built in GeoCom interface. A routine was developed to tilt the device in predefined positions. To attach the phone to the total station, it has been fitted with a mount and balance weights. Figure 2. shows the modified device.

Figure 2. Leica TCRA 1105 plus with adapter

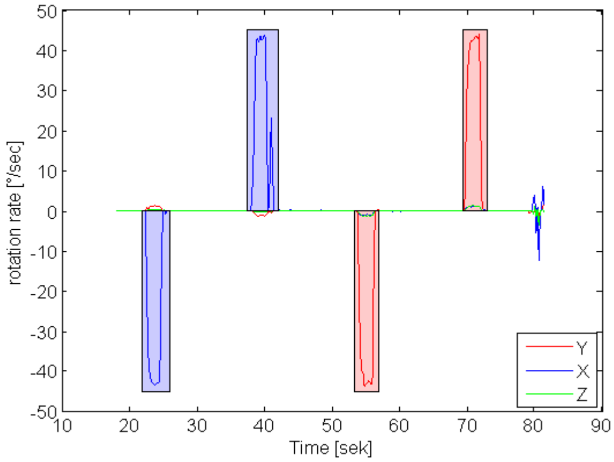

Figure 3. Mearusrment with the tillting method

For the analysis, the following five positions have been deposited in the program; vertical (VZ) 0 ° horizontal (HZ) 0 °/ 90 ° VZ, HZ 0 ° / 0 ° VZ, HZ 0 ° / 0 ° VZ, HZ 90° / 0 ° VZ , 0 ° HZ. Figure 3 shows an example of a series of measurements and their analysis in ° / sec.

A scale of 1.011392 ± 0.0016 for the x-axis (VZ) and 1.006902 ± 0.0018 for the Y-axis (HZ) is determined out of eight series of measurements. Here, it should be noted that the magnitude principle is used to determine the parameters. Thereby the cross coupling is eliminated, which is clearly visible in all test series. The cross coupling error resulted largely from the mounting of the smartphone, because the rotational axes and the coordinate systems do not coincide. A clear definition of the smartphone coordinate system is hardly possible, since even the display has a curved surface. Since this method of determining the exact start and end points of the tilting-process is difficult, this method seems to be quite inaccurate. In addition, the signal must be integrated for calibration, thus the noise is also integrated and that could lead to a distortion.

2) *Scale determined by rotation*

So another way to calibrate the sensor was looked for. Here, the total station provides yet another possible solution. The drive of the total station will also be controlled directly by the GeoCom interface. The rotational speed of the motors (vertical and horizontal) can be specified in radians per second. The used total station allows a maximum angular velocity of about ± 40.0 ° / sec (± 0.7rad/sec), a current total station like Leica TM 30 allows angular velocity of about ± 170.0 ° / sec (± 3.0 rad / sec). The program was developed to control the total station and was adapted to rotate a total station at an adjustable angular velocity. A routine operates the measurement, so that the working range of -40.0 to + 40.0 ° / sec run through with a step size of 5.72 ° / sec (0.1rad/sec). However, the system can rotate only the vertical axis, because of the mounting system on the telescope, this allows no rotation about the horizontal axis. The predefined speed is maintained for one minute, and then stopped for one minute. For reasons which will be discussed later, the interval for the measurements is subsequently been reduced to 20 seconds.

The angular velocity is set via the GeoCom interface and had to be checked, because of the additional structure on the total station and the lack of knowledge concerning the quality of the engine. This can be considered in three ways. The first idea involves a camera (Canon 50D). The integrated visible Laser from the total station can be monitored at different angular velocities. The laser beam can be observed at a known distance to the total station on a white wall using a camera and a defined exposure time. The angular velocity can be calculated from the length of the laser spot (strip) from the images. The second option replaces the camera by a photosensitive diode with an electronic time clock. A timestamp is set with each rotation, producing the angular velocity of 360°. This possibility has not been implemented. The third idea involves the tracking of a spherical reflector (CCR 0.5 inch) in eccentric position on total station. To realize the idea a "Leica AT 901 Laser Tracker" was used. This measurement system has an accuracy of 3D points of 10µm at close range and allows up to 1000Hz for time-dependent measurements. The internal timing has a resolution of 1MHz (1µs) and a drift of <20µs/s. Figure 4. shows the experimental setup. The laser tracker monitors the Total Station from far up as possible to avoid rotations of the reflector. The total station rotates and is observed with the laser tracker. Measurements are made every 3 seconds and 10 seconds. A sampling rate for the point measurement of 100 Hz and 1000 Hz is used. The angular velocity is calculated from an adjustment of a circle from the measured points of each period (3 seconds or 10 seconds), the start point and the end point and the measured time. Velocities from 0.1 to 0.6 rad / sec have been analyzed.

Figure 4. Experimental setup calibration totalstation

The quality of the determined angular velocities depends largely on the quality of timing and the accuracy of the measurement from the laser tracker. With a single-point accuracy of 10 µm and with a radius of 62 mm, a maximum angle error of 0.16 mrad is to be expected. Using the example of 0.1 rad/sec and 3sec measurement time, the angular velocity error would be 0.05 mrad/s. Longtime measurements and higher rotational speed have less influence on these errors. The existing drift (<20µsec) is taken into account in the quality of the time measurement. This error is different to the measurement accuracy of the laser tracker especially on long observation periods and high rotational speed. The deviation of the rotational speed is for a 10 sec observation period and 0.6 rad / sec at most 0.01 mrad / sec. The following TABLE III. shows the angular velocities compared to reference value.

TABLE III. COMPARISON OF THE ANGULAR VELOCITIES

reference (rad/s)	***observed (rad/s)***	***difference***
0.1	0.0962	-0.0038
0.2	0.1925	-0.0075
0.3	0.2884	-0.0116
0.4	0.3843	-0.0157
0.5	0.4810	-0.0190
0.6	0.5775	-0.0225
Scale	0.9629 (±0.0008)	

The velocities determined by laser tracker are reproducible with an accuracy of 0.5 mrad / s, as shown by multiple measurements. Compared to the previously derived theoretical accuracies, it is less accurate by a factor of 10. A reason for this could be the measurement setup. There were some very oblique angles measured on the reflector necessary to prevent breakage of the measurement process for a time period. In some measurements, the reflector had to be rotated manually. It can't be neglected that the drives themselves have deviations. The achieved accuracy of the angular velocity should be sufficient for a review of the gyroscope. A scale of 0.9629 was derived from the measurement data with a standard deviation of ±0.0008.

The first series of measurements was recorded using the total station as it is shown in Figure 5. The blue curve defines the reference during the period, while the green curve represents the measured values. The green curve differs significantly from the blue curve. The smartphone resets after about ten seconds at a constant angular velocity the measuring signal back to zero. This effect is caused by a filter or a Zero Velocity Update (ZUPT). This shows that at no change in angular velocity of the measured deflection is interpreted as a measurement error. This is corrected internally. The same phenomenon appears when the measuring program stops the total station. Then the measurement signal proposes in the opposite direction. After about ten seconds this true measurement error is detected and reset.

It cannot yet be fully resolved, in which level this filter works. Either it is programmed directly on the MPU 3050, or it is a function of the operating system that can't be affected. The monitoring program that records the sensor data from the smartphone, works as a simple app(-lication). The app accesses the sensor interfaces which are provided by the operating system, for further explanations look at the Android SDK [13]. Only for ten seconds a usable signal can be recorded. Therefore, the measuring time has been limited to 20 seconds to that the amplitudes are recorded correctly.

Another critical factor is the time unit. The Android API provides three time functions. Of which two are used to provide the measured values with a time stamp. The standard time, which works exactly to the millisecond and the nano time stamp is available. For measurements the Android Developer Guide strongly recommends the nano time stamp; it says „Returns the current timestamp of the most precise timer available on the local system." [14]

The drift of the time system will not be discussed further at this point, but will be the subject of future investigations.

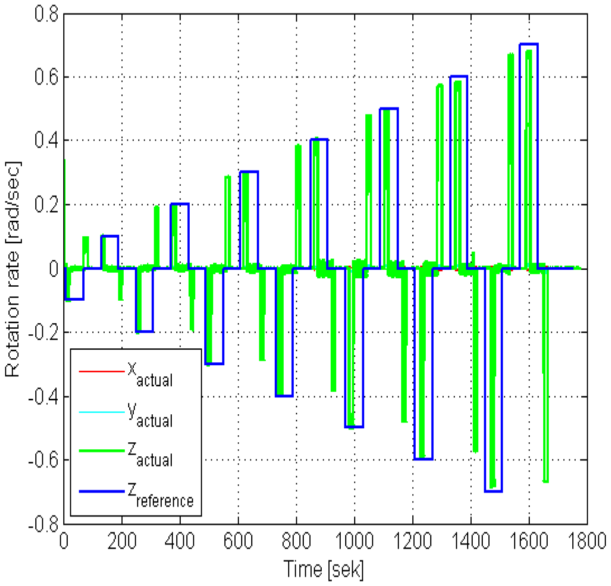

Figure 5. First series of measurement without scalefactor

Several series of measurements at different rotation speeds were recorded. A series of measurements was taken with a calibrated sensor, the Xsens MTi-G, to verify the results. This system is used for example in UAVs (unmanned aerial vehicle). The angular velocity is the mean of the signal at the preset speed. The noise of the smartphones is about 0.33 ° / sec, the MTi-G has a significantly higher noise at about 0.60 ° / sec. The Phone 1 + 2 are representing the Samsung Galaxy Nexus and Phone 3 is an older model of Samsung. TABLE IV. shows the results as a linear function for scale and offset.

TABLE IV. RESULTS OF THE MEASURMENS

Sensor	**count**	**Scale**		**Offset**	
		value	***dev.***	***value [°/sec]***	***dev. [°/sec]***
Phone 1	10	0.992412	0.000069	-0.010672	0.010156
Phone 2	10	0.995157	0.000111	-0.012416	0.022138
	10[a]	0.994616	0.000192	-0.007025	0.038450
Phone 3	1	0.997747		0.004823	
Xsens MTi-G	1	1.004516		-0.099162	

a.two days later

As TABLE IV. shows, all scales are relatively constant. Compared to the reference measurement with the laser tracker it is noticeable that all the examined Smartphones have a smaller scale, while the Xsens has a larger scale. No significant offset can be derived from the multiple measurements with the three phones.

In the following the drift of the sensor is examined. Figure 6. shows the ten test series in chronological order. Each blue line represents the deviation from the mean of the angular velocities of ten measurements. The studied area is between - 40.10 ° / sec and + 40.10 ° / sec, with a step size of 5.72 ° / sec, so there are 14 lines. This series of 10 measurements takes about 124 minutes, thus slightly longer than the actual measuring time of 94 minutes, because of breaks between the measurements. Basically, it should be noted that the smartphones have a different variance. The reasons for this are not revealed yet. Consideration should be given, that the phone 2 is in daily use and Phone 1 is only used for measurements and application development.

Figure 6. shows a drift in the data. A linear function was determined for both data sets. TABLE V also gives gradient and offset. If the drift is extrapolated to one hour, Phone 1 has a drift of 0.02 °/h and Phone 2 0.04°/h. This is the same accuracy class as the Xsens MTi-G. The drift can’t be revealed, but a guess is the heating of the device, this is explicitly addressed in the next section. However, according to information from the data sheet a temperature sensor is built in the MPU3050 to stabilize the temperature. But this works probably at the sensor level and remains hidden from the user.

TABLE V. SENSOR DRIFT

Sensor	***Gradient [°/sec]***	***Drift [°/h]***
Phone 1	0.003345	0.02
Phone 2	0.006719	0.04

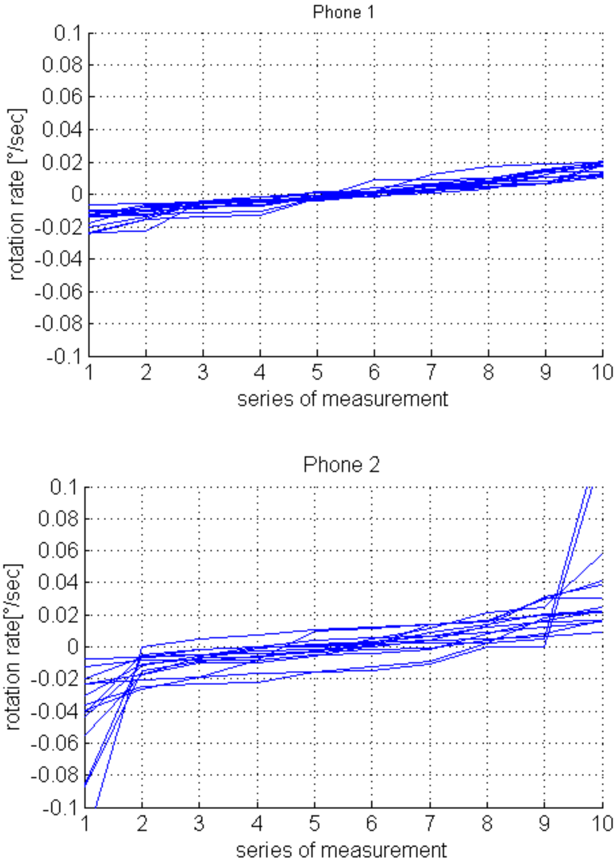

Figure 6. Drift and variance of the sensors

The calibration values determined in this paper were tested on a real example. For this, a navigation application was used, which is developed at the HCU. No aiding information and filter has been used for the evaluation. The trajectory was calculated with the gyroscopes and accelerometers of the smartphone. The accelerometers do not have the quality that is required to calculate the translation from the integrated accelerations as usual in inertial navigation systems. Therefore, a step detection [11] was used. From the acceleration data, the steps are detected and counted, and in addition with a mean step length this provides information about the translation. A simple dead-reckoning was performed with steps and angles [12]. A single track was recorded in the building with the Phone 1. This track was processed during the recording and was stored on the smartphone. This is shown in Figure 7 as a blue line. Overall, the track is about two minutes, even within this short time the typical drift of the gyroscopes can be detected. In the post-processing the measurement data is corrected by the scale factor and offset and shown in Figure 7 as a green line. The improvement is clearly visible. The drift of the sensor, however, still dominates the trajectory.

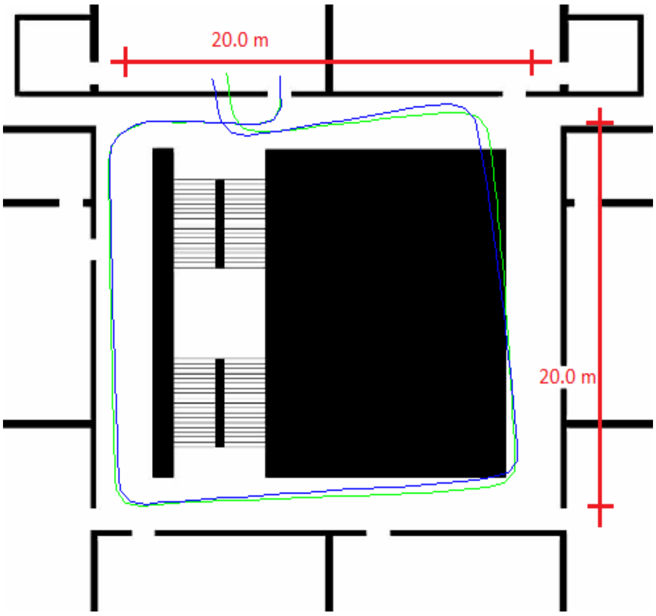

Figure 7. Sample of Dead Reckoning (blue without scale, green with scale)

For comparison between calibrated and non-calibrated data as an example the second 90-degree turn is used to compare the angles. A rotation of 99.007 ° is calculated in the non-calibrated data, wherein the rotation from calibrated data is in the same period 96.945°. The correction here is 2.062°

B. Barometer

As the barometer is a very new sensor in smartphones no calibration will be performed for this at this time. First its performance and compliance with the manufacturer's specifications should be checked. A fundamental question for the use of the sensor in the indoor navigation is the suitability of the barometer to the storey identification. For this purpose, a simple series of measurements in the staircase of a building at the HCU Hamburg has been taken. The staircase consists of 4 storeys. The maximum difference in height is 12.80m. The storeys were passed out in the order 4-3-2-1-1-2-3-4. Data was recorded on each storey for four minutes. Figure 8. shows the series of measurements with the desired height, the mean values and the uncertainty (95%). The first measured value of air pressure was taken as the reference pressure for conversion into heights.

The manufacturer Bosch gives the typical operating range of 950-1050 hPa and a relative accuracy of ± 1.0m (0.12 hPa). The analysis in Figure 8. confirms the manufacturer´s information. The mean deviation is 0.1 m with an uncertainty (95%) of ± 0.85m. Finally, it may be mentioned that the storeys can be readily separated from each other and the sensor works in its specifications.

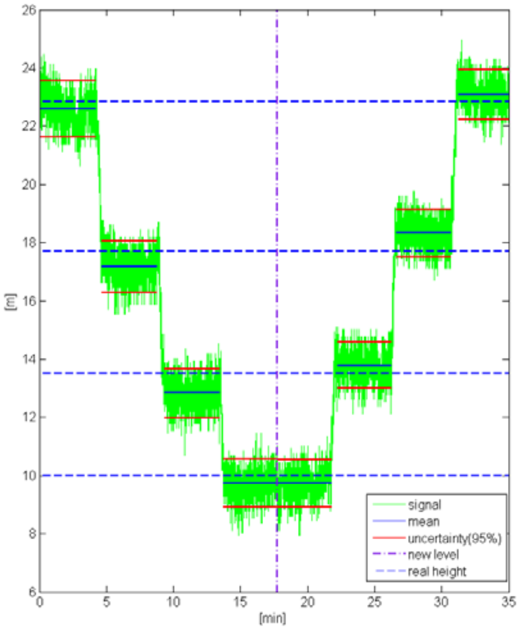

Figure 8. Measurement with Barometer

A significant heating of the device are always determined during the test series. Since all the sensors respond to temperature changes, this could lead to a distortion of the measured values. The barometer sensor BMP-180 in addition to the pressure sensor itself has also an integrated temperature sensor. This sensor can’t be addressed via the Android API. It only serves the correction to the barometer. According to Bosch on-chip calibration data are stored, so the microcontroller of the barometer makes a correction of the measured pressure using temperature and calibration data. To investigate the behavior more accurately, the measurement data of the smartphone were compared with reference data. As a reference for the air pressure a Setra B470T was used with an absolute accuracy of ± 0.02% at range of 800 to 1100 hPa (300 hPa => 0.06 hPa (0.5 m) deviation). In addition, the temperature was detected with two PT100 probes. The first probe registers the ambient temperature, while the second was attached to the phone in order to measure the housing / sensor temperature. In Figure 9. the measured data is shown. The measurements with the phone were in the entire period above the reference data. Furthermore, it can be shown that the increasing of the temperature on the smartphone body of about 4 ° C while the reference temperature decreases slightly.

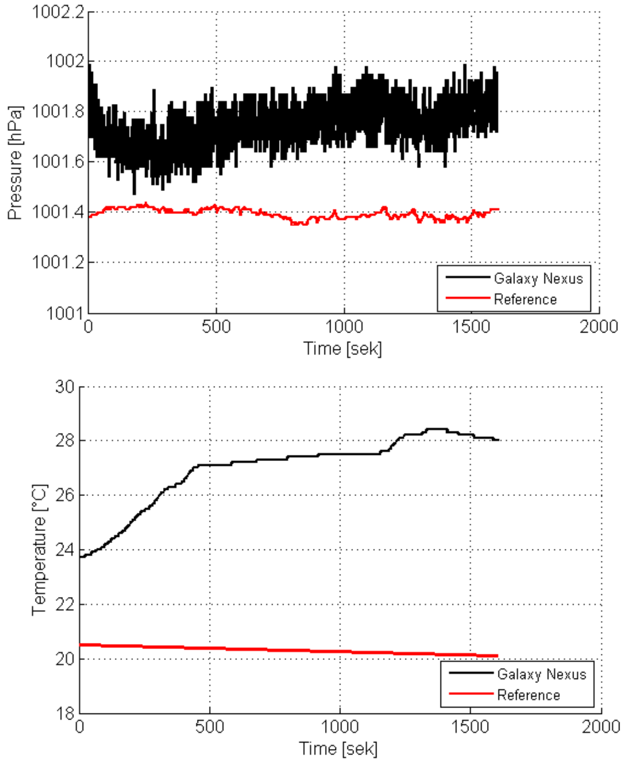

Figure 9. Barometer of the Smartephone in comparison with a accurate SETRA barometer and two temperature sensors

A correlation of case temperature with the air pressures of the smartphone gives the correlation coefficient of -0.86. This means a high opposing dependency of both values. Furthermore, the determined air pressure reacts about 3.3 min before the temperature changes at the case could be measured. This could partly be explained with the delay of the temperature change through the case. For better interpretation Figure 10. shows the temperature on the Samsung Galaxy Nexus case with the measured air pressure values in a higher resolution.

IV. CONCLUSION AND OUTLOOK

Developments in smartphone technology have changed the research and development for indoor navigation. Current smartphones have built-in sensors that make indoor navigation possible, without resorting to backpack systems.

This paper describes an approach for calibrating a gyroscope, which is integrated in a phone, using a total station. The total station provides a rotational speed constant enough to perform the calibration. The predefined angular velocities aren`t reached, because of the extra weight of the telescope. Therefore the angular velocities from total station are calibrated with laser tracker. However, the application example shows that the system-related disturbances of the gyroscope like sensor-drift and random-walk affect or even dominate the navigation solution. The authors conclude that the achievable improvement is large enough to confirm that a single calibration of the sensors sufficed. The temporal calibration stability can be estimated from the calculated standards of phone2 (Table IV: 10,10a). These indicate a distance in the scale of 0.0005 with standard deviations of less than ± 0.0002 to each other. Should different smartphones of the same type provide similar results, the correction can be made in the form of a type calibration. For correcting sensor drift an alignment can be performed directly prior to each use of the smartphone. Therefore the smartphone should stay at an inoperative state. Afterwards the scale and offset can be determined.

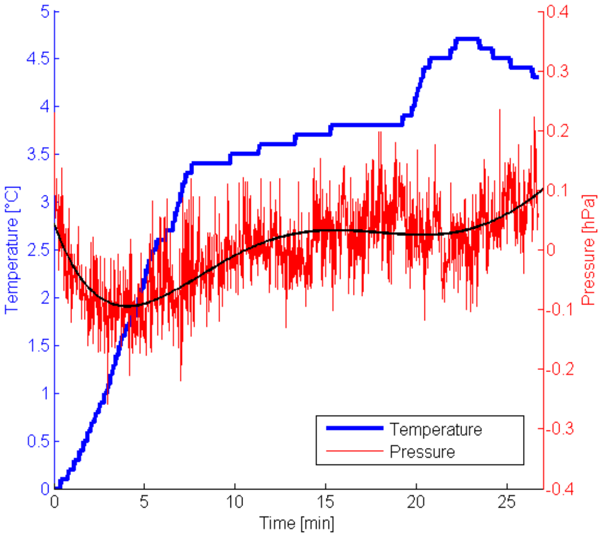

Figure 10. Temperature of the Smartphone housing and measured pressue, shows a opposing dependency (correlation -0.86, delay 3.3 min)

The studies of the integrated barometer of the Galaxy Nexus show that individual storeys of a building can be identified from air pressure measurements. The measurement uncertainty (95%) of 0.85 m derived from the measurements is slightly lower than the manufacturer's instructions. However, the dependence on the smartphone temperature is clearly visible. A heating of the device can thus lead to misinterpretations. Further studies on the behavior of the barometer and other sensors will follow regarding the smartphone temperature. A further step will be to examine the possibilities of the accelerometer in indoor navigation. The data from the accelerometer from previous MEMS sensors have at best serve as a pedometer. It is to consider, how the accelerometers can be used for short distances for a speed measurement or for a detection of the stairs steps. Furthermore, the holding of the position by detected air pressures of the barometer of interest. The results show that a change of the storeys can be detected relatively easily. With the knowledge of the relative traveled distance or a known gradient of the stairs/ramp a position can be interpolate by the determination of a change of height by air pressure. It has been shown that the calibration of the sensors can be performed with simple and cost-effective means. The increase in the accuracy is large enough to justify the calibration.

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