RESEARCH-ARTICLE

On the (In-)Accuracy of GPS Measures of Smartphones: A Study of Running Tracking Applications

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On the (In-)Accuracy of GPS Measures of Smartphones: A Study of Running Tracking Applications

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ABSTRACT

Sports tracking applications are increasingly available on the market, and research has recently picked up this topic. Tracking a user's running track and providing feedback on the performance are among the key features of such applications. However, little attention has been paid to the accuracy of the applications' localization measurements. In evaluating the nine currently most popular running applications, we found tremendous differences in the GPS measurements. Besides this finding, our study contributes to the scientific knowledge base by qualifying the findings of previous studies concerning accuracy with smartphones' GPS components.

Categories and Subject Descriptors

H.3.4 Systems and Software: Performance evaluation (efficiency and effectiveness)

General Terms

Performance

Keywords

Location-based System, GPS, Global Positioning System, Accuracy, Smartphone, Sports Tracking, Running Tracking, Localization, Positioning

1. INTRODUCTION

Globally, the number of smartphone users topped one billion at the end of 2012 and is estimated to double in less than three years [18]. Spurred by Apple's and Google's platform concept, the development of mobile applications is booming; about 1.7 million total applications had been created by the end of 2012 [2]. The use of smartphones is far beyond its classic domain of application, as applications for all purposes have turned the smartphone into a multi-functional device that pervades everyday life [12]. There are applications for every flavor: games, news, guitar tuners, wine guides, maps, messengers, travel booking, etc. This trend is also visible in the sports domain, in particular for running – a topic that

is also increasingly getting attention in research [e.g., 1, 4, 15, 17].

Among other features, most running applications include tracking a user's running track and providing feedback on the performance with respect to the distance run and altitude differences. Typically these figures are visualized with route mapping and diagrams (Figure 1). The basis for this feature is rooted in location technologies, which can be considered standard components in today's smartphones: Cell Identifier (Cell ID) based positioning, localization via Wireless Local Area Network (WLAN), and localization via Global Positioning System (GPS) [13, 16, 26]. For sports tracking – in particular, when in competition with other athletes or for benchmarking, a feature that most running applications offer – the expectation of users is to receive accurate tracking information [7]. As a result, WLAN or Cell ID based tracking are not sufficient for these applications' purposes because their positioning results are not fine-granular. Due to its precision, and worldwide availability [13] without the need for additional infrastructure [7], GPS is considered the most suitable candidate for sports tracking applications [7].
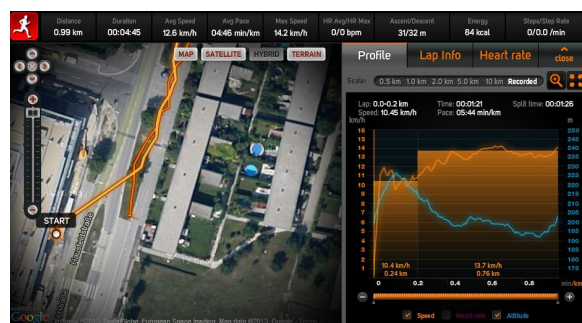

Figure 1. Visualized Running Track (left) and Altitude Differences (right).

However, current smartphones contain very basic GPS receivers [26]. As a result, the deviations may be larger compared to high-quality GPS receivers [6]. As smartphones are equipped with different chip sets, accuracy levels also depend on the respective devices [25]. Research on measurement accuracy has been performed to analyze differences between smartphone devices [14, 25], between platforms [7], between localization technologies [26], or between GPS based tracking with a smartphone and a high-quality GPS receiver [16].

In an explorative study analyzing the features of running applications, we found that identical hardware and platform setup,

as well as positioning method (using GPS that is embedded into the smartphone), delivered different tracking results for different GPS based applications. Having delved into detail on this finding, this paper presents the results on the measurement accuracy of the nine currently most popular running applications.

The next section provides background information on location technologies embedded in smartphones and discusses related work, comparing different positioning modalities with respect to method and hardware. Section 3 outlines the procedures of our comparison study. In Section 4, we present the results concerning deviations in lengths of distance and altitude differences as reported by the analyzed applications. Section 5 discusses our findings and concludes with an outlook on future research.

2. BACKGROUND AND RELATED WORK

2.1 Location Technologies in Smartphones

Location based services (LBS) are services that are accessible through mobile networks and use the geographical position of a mobile device [24]. The initial attempts in the field 'context-aware computing' produced a plethora of LBS services [21], mainly due to the fact that devices, at that time, had limited physical-sensing capabilities and were largely confined to a device's location. With the miniaturization of hardware components and proliferation of smartphones, LBS have become ubiquitously available to consumers [7] and emerged as an important component of mobile commerce [19].

Considering the vast availability of LBS applications, we observe different degrees of granularity and accuracy, and different requirements on how frequently to refresh location information to serve the applications' purposes. While for some applications a rough estimate may be sufficient, others require more accurate information [25]. For instance, using the application Foursquare, people can communicate their current location and their location history in terms of 'business premises', 'restaurants', 'bars', etc. The granularity of data required is rather low, as is the needed frequency for updating localization information. In contrast, other applications, such as those for car navigation, require high accuracy and frequent location updates to ensure reliable routing. In events such as sports competitions, very precise and accurate positioning information is necessary, which also requires frequent location updates [7]. To illustrate, Dobson [5] provides a non-exhaustive list of 18 different ways to gather location information with different grades of accuracy, depending on the need and purpose of localization.

Three main location technologies are integrated as standard components in today's smartphones: Cell ID, WLAN, and GPS [13]. Also note that other sensors can be creatively deployed to sense location, going beyond their primary sensing purposes – for instance, using a smartphone's microphone for indoor positioning [e.g., 20].

Cell ID based localization works as long as there is mobile network coverage that the smartphone can connect to. The position of the device is derived from the coordinates of the serving base station [26]. It is accurate within hundreds of meters of deviation only. Cell ID information may be combined with a rough estimation of the round trip time between the device and base station (so-called 'timing advance value'), from which the range between them can be derived. With this combination, position fixes of higher accuracies can be achieved [13].

The localization with WLAN is based on measuring the proximity of a mobile device to wireless access points via the intensity of the received signal (received signal strength; RSS). RSS patterns that are received at several access points are compared with a table of predetermined RSS patterns collected at various positions; the location in the comparison that fits best is adopted as the device's position [13, 26]. Based on this mechanism, WLAN based positioning is accurate within 30 to 50 meters deviation and works indoors and outdoors [26]. However, as this technology requires the availability of a wireless hotspot to register in, it is limited to densely populated areas [13, 26].

The GPS is a satellite based navigation system developed by the U.S. Department of Defense for military purposes [6]. It allows locating mobile devices at any place, any time on Earth using trilateration with range measurements between an observer and a few visible satellites [6]. At least four independent measurements (satellites) are required for computing a fixed position [10]. While the military GPS version is able to provide more accurate positioning data, its public version is limited to an accuracy of up to 5 to 10 meters [8, 13]. This accuracy level can also be achieved with low-cost GPS receivers, such as the ones integrated in smartphones, when locked onto the minimum number of satellites [10]. The functionality of GPS is, though, limited to outdoor positioning as line of sight to the satellites is required [13]. Although the prevalence of GPS receivers has dramatically driven down cost, size, and power requirements [6], GPS sensing is, compared to other location technologies, rather resource intensive [3, 9].

2.2 Studies on Smartphone Tracking

Measurement accuracy using GPS that is embedded in smartphones has been the subject of many research endeavors. Menard, Miller, Nowak and Norris [14] analyzed capacity differences in GPS based positioning in smartphones (using three different smartphones: Samsung Galaxy S, Motorola Droid X, and iPhone 4) compared to a vehicle tracker. They concluded that the three smartphones were an acceptable alternative to other tracking devices in vehicles. They showed that each smartphone was accurate within 10 meters about 95 percent of the time.

The differences in positioning accuracy among different Apple devices (iPhone, iPod Touch, and iPad) have been researched by von Watzdorf and Michahelles [25]. They found significant differences in accuracy. However, the different devices under study used different location technologies, too (WLAN versus a combination of WLAN, GPS, and Cell ID). In contrast, Zandbergen [26] evaluated the differences between GPS, WLAN, and Cell ID based positioning by using only one device (iPhone 3G) and one application. He found that the WLAN method has potential for indoor positioning, but outdoors it lags behind compared to GPS based localization.

Using a self-developed LBS application, Hess, Farahani, Tschirschnitz and von Reischach [7] compared different smartphones with different operating systems (Android 2.3.3, Android 2.3.6, iOS 4.2.1, iOS 4.3.5, and Windows Phone 7) with different GPS chipsets. They concluded that GPS measurement accuracy heavily depends on the respective smartphone.

Kost and Brčić [11] analyzed GPS positioning errors based on weather conditions on two different smartphone devices for one fixed position, concluding that the research community should consider that positioning accuracy depends on various factors, such as space weather related error components.

Mok, Retscher and Wen [16] investigated whether a combination of different sensors that are embedded into smartphones could assist GPS positioning to increase the accuracy level. They found

that, assisted by an accelerometer and digital compass, GPS positioning accuracy could be improved.

To the best of our knowledge, though, different tracking applications run on a single device (and having the same setup for each application) has not yet been researched.

3. RESEARCH DESIGN

In this work, we analyze nine currently popular running applications that use GPS based localization in real time while moving (running). The objective is to compare them with respect to the accuracy of localization measurements.

3.1 Sample

We chose Android for our study for being the platform with the highest market share (approximately 80 percent in 2013 [23]). In order to reflect the highest quality and most popular applications available at the time of our study, we considered those applications with the highest download rates and user ratings in the Google Play Store.

As the Google Play Store does not offer a specific running or sports category, we had to manually search for applicable applications in the 'health and fitness' category and compare their download rates and ratings.

We chose the top nine free applications (minimum of one million downloads by 31-May-2013) as a representative sample for this evaluation (Table 1). The user rating of all applications in the sample was high (on average 4.3 stars and above). We had to exclude the application 'Nike+ Running', which was among the top ten, because it was not compatible with our available testing device (HTC Desire Bravo).

Finally, we made sure from their descriptions that the applications relied solely on GPS for tracking the user (i.e., they do not combine it with further localization technology).

Table 1. Sample description

Application	Downloads in millions	User rating	Last actualization
Endomondo	5-10	4.5 (109081)	21-May-2013
Runtastic	5-10	4.6 (76234)	26-Apr-2013
Noom Cardio Trainer	5-10	4.4 (53699)	11-Jan-2012
MyTracks	5-10	4.4 (75482)	17-Apr-2013
Runkeeper	1-5	4.5 (57992)	23-May-2013
Sports Tracker	1-5	4.6 (48275)	16-May-2013
MapMyRun GPS Running	1-5	4.5 (33468)	10-May-2013
Adidas miCoach	1-5	4.4 (16583)	10-May-2013
Orux Maps	1-5	4.6 (9808)	21-Apr-2013

3.2 Testing for Accuracy

All applications were tested with the smartphone model 'HTC Desire Bravo', following the same procedure for each application. For applications that allowed using other means for localization (e.g., Sports Tracker), the respective technology was disabled to ensure that only GPS data is considered.

First, a distance of exactly 500 meters was measured in a highly populated (city) location, so that running back and forth along this track in a straight line would result in a total distance of exactly

one kilometer. As the starting and ending points were the same, the altitude difference between them was ensured to be zero.

Second, a test person ran the measured track back and forth in a straight line, with each of the applications in the sample. Before the start of every run, the GPS signal was ensured to be good enough for adequate measurement (which is a feature of most running applications). After a run with an application, the application itself and the Web interface that extended the application (if available) were checked for the total distance of the run (the result of which should have been one kilometer) and any altitude differences (which should have amounted to zero). Additionally, we analyzed the visualization of the tracked routes in the application, as these gave good indications about the accuracy of the tracking measurements.

4. RESULTS

4.1 Distance

Table 2 shows the measurement data of all applications for distance in alphabetical order. Figure 2 visualizes the distance inaccuracies, sorted according to deviation.

Table 2. Accuracy measurements for distance

Application	Distance in meters	Deviation in meters	Rank
Adidas miCoach	1000	0	1
Endomondo	940	60	8
MapMyRun GPS Running	1030	30	6
MyTracks	1030	30	6
Noom Cardio Trainer	1010	10	2
Orux Maps	1010	10	2
Runkeeper	980	20	5
Runtastic	940	60	8
Sports Tracker	990	10	2
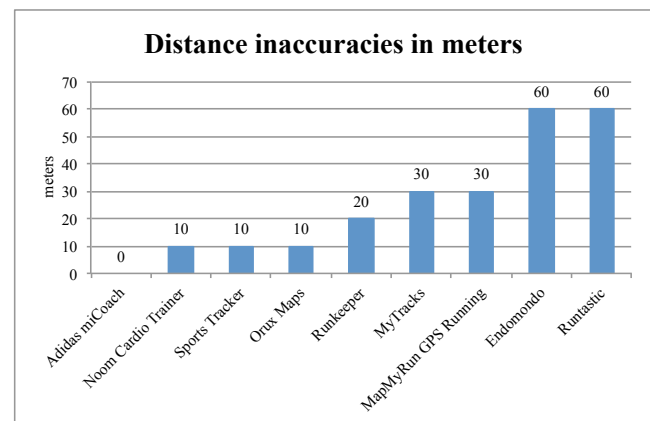
Figure 2. Distance inaccuracies.

Only one application (Adidas miCoach) measured a total distance of one kilometer. Noom Cardio Trainer, Orux Maps, and Sports Tracker showed deviations of 10 meters each. Runkeeper was 20 meters off. MyTracks and MapMyRun GPS Running were off by 30 meters. In comparison, Endomondo and Runtastic showed a

deviation in terms of distance that was more than double those of the other applications (60 meters). As is illustrated in Figure 3, Endomondo's measurement was far from a straight-line running track.
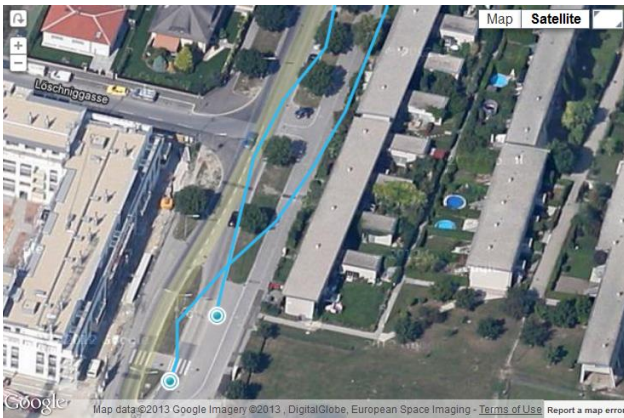

Figure 3. Endomondo's tracking data shown on Google Maps.

4.2 Altitude Differences

The measurements for altitude differences had to be unified in order to be comparable. Some applications divided into ascent and descent measurements; accordingly these figures were added up in order to get the total deviation. Other applications only provided absolute altitude differences gained (ascent measurements), which meant negative altitude differences were not shown in the applications. Assuming that ascent and descent measurements must be equal when a track is run back and forth, we compensated the missing data for descent with the equivalent for ascent. (We are aware that ascent and descent measurements may be prone to different measurement problems; since some of the applications did not report negative altitude differences, we had to act on assumptions.)

Table 3 shows the measurement data of all applications for altitude differences in alphabetical order; estimates are given in italics. Figure 4 visualizes the ascent and descent data, sorted by total altitude deviation.

Runtastic and Noom Cardio Trainer tracked the elevation correctly. Runkeeper, Adidas miCoach, MapMyRun GPS Running, and MyTracks were slightly inaccurate, with deviations ranging from 8 meters to 14.58 meters. Orux (27 meters) and Endomondo (33 meters) delivered measurement inaccuracies that were more than double those of other applications measured. And worst of all, Sports Tracker doubled those inaccuracy measurements, reporting 63 meters of deviation.

Table 3. Accuracy measurements for altitude differences

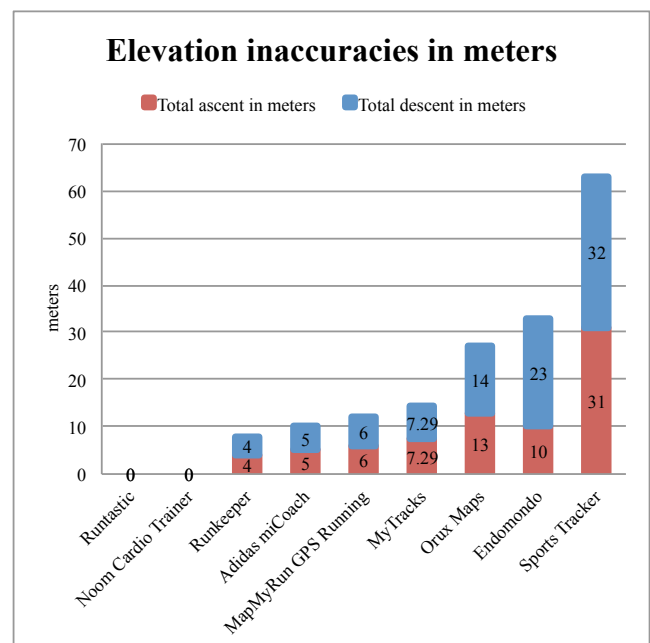| Application	Total ascent in meters	Total descent in meters	Total deviation in meters	Rank
Adidas miCoach	5	*5*	10	4
Endomondo	10	23	33	8
Noom Cardio Trainer	0	0	0	1
MapMyRun GPS Running	6	*6*	12	5
MyTracks	7.29	*7.29*	14.58	6
Orux Maps	13	14	27	7
Runkeeper	4	*4*	8	3
Runtastic	0	0	0	1
Sports Tracker	31	32	63	9

Estimates are given in *italics*.

Figure 4. Elevation inaccuracies.

4.3 Total Deviation

Summing up the distance and altitude inaccuracies for each application, Figure 5 represents a clear picture of the potential for improving tracking accuracy.

The deviation levels of Noom Cardio Trainer and Adidas miCoach show only slight deviations (10 meters each), while Endomondo presents the highest total deviation measurement with 93 meters.
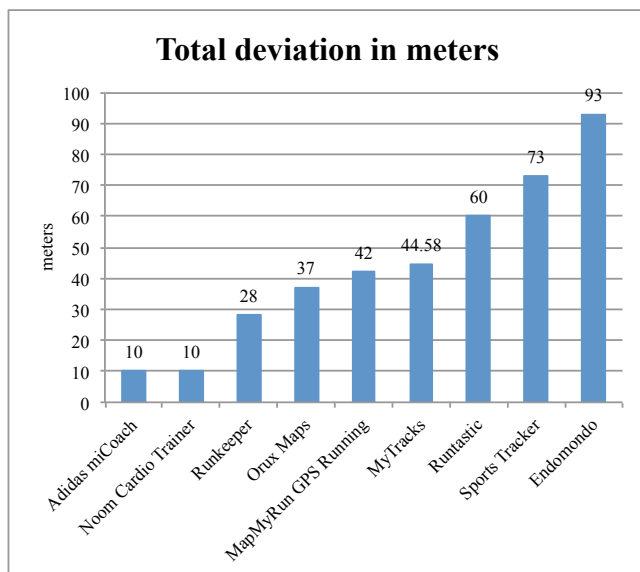
Figure 5. Total deviation in meters.

5. DISCUSSION AND CONCLUSION

In this paper we presented a study that compares the GPS based measurements from nine different running applications on a single smartphone, measured on the same track of one kilometer in an urban area. The deviations between the distances and altitude differences measured by the applications were tremendously high. While the different accuracy levels firstly indicate a quality ranking of the analyzed applications, this study additionally contributes to the scientific knowledge base by qualifying the findings of previous studies in the field.

Our study results show that GPS delivers different results on the same device. Accordingly, the findings of Menard, Miller, Nowak and Norris [14] have to be handled with care. The differences that they found in their study cannot be directly attributed to the different GPS components used in the analyzed devices.

Moreover, the differences in positioning accuracy found by von Watzdorf and Michahelles [25] may basically be due to the different location technologies used for each device setting (WLAN versus a combination of WLAN, GPS, and Cell ID). This implies that their setup varied by the involved sensing hardware and employed technology, causing biased results because their findings on accuracy can neither be directly attributed to a specific technology nor to a specific hardware setup.

Zandbergen [26] used a single device research design to analyze differences between GPS, WLAN, and Cell ID based positioning. In our study, however, GPS delivered different results for each analyzed application. Accordingly, the 'ranking' of these technologies' accuracy levels has to be handled with care.

Hess, Farahani, Tschirschnitz and von Reischach [7] conclude in their study that GPS measurement accuracy depends on the respective smartphone. Similar to the study by von Watzdorf and Michahelles [25], the study setup – mixing hardware (GPS chipsets) and platforms – does not allow for conclusions concerning the devices, as the operating system may also have influenced the results. In addition, we show in our study that GPS measurements on a given device may vary with the application.

Although we show that previous work has limitations, we appreciate these studies' contributions to the knowledge base, as they provided first indications in the field and triggered further research with respect to combining location technologies to deliver more accurate results [e.g., 16, 22].

Our work also faces limitations. Firstly, we did not control for crowdedness and traffic when tracking the locations. Also, the phones' internal activity (lowering read out frequency) as well as temporary surrounding influences, such as the reflection of signals disturbing GPS reception, cannot be excluded as influencing factors. Differences with respect to these issues may have influenced the GPS measurement results, causing more deviations for some applications and less for others. Future work should control for this; it may, for instance, be addressed by running the track several times with each application. Alternatively, one runner could wear 9 phones of the same type, each running one of the apps. Secondly, we did not control for space weather influence, such as Kos and Brčić [11] did rigidly. Thirdly, we tracked a rather short distance of one kilometer. It is still unclear how measurements develop over long distances. If, for instance, Endomondo would keep its deviations per kilometer, a marathon (42.195 kilometers) would result in a deviation of 2531.7 meters. For a runner that maintains a pace of 5 minutes per kilometer, that would distort his/her performance by 12.6585 minutes. For casual runners and short distance tracks, that might not be an important issue. On the other hand, for runners preparing for a marathon, such a deviation is not acceptable as it can cause severe health problems. As a result, longer distances should be evaluated in future investigations.

In conclusion, this paper provided an overview of the currently most popular running applications for smartphones and evaluated them for measurement accuracies with GPS. We identified deviating results for each application, which implies influencing factors on GPS accuracy apart from GPS component and location of the track, which were held constant for the study. As previous studies did not emphasize this issue, we suggest that future work should pay more attention to these influencing factors.

6. ACKNOWLEDGEMENTS

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