Mitigating GPS Error in Mobile Environments

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Technical Report CS-2008-13

July 14, 2008

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Abstract. We study the problem of accurately determining the position of a mobile device using imprecise off-the-shelf GPS devices. Existing work has not yet explored the impact of mobility on GPS error for off-the-shelf devices. We demonstrate that a naive use of GPS in mobile situations can lead to significant errors. Based on both stationary and mobile vehicular experiments, we identify four distinct sources of measurement error, resulting in a surprising 49.0 m of error while traveling at highway speeds of 100 km/h. We quantify the error into systematic error (44.7 m) and random error (4.3 m). We also show how simple techniques can significantly reduce systematic error, yielding up to a ten-fold reduction of error in mobile GPS measurements. We find that mobile error is primarily caused by misreporting *when* position measurements were taken and *infrequent* measurements. After correcting for these errors, off-the-shelf devices can be used for accurate position measurement while mobile.

1 Introduction

GPS is the most widely used outdoor locationing system and is used for vehicular collision avoidance [1, 2], automated vehicle control [3], and in-vehicle navigation [4]. GPS is also commonly used to track device position in mobile computing research [5–8]. Yet, GPS suffers from inherent imprecision due to a variety of factors. Moreover, as we will demonstrate, the degree of imprecision increases with increased vehicle speed. Reducing measured position error is obviously critical for collision avoidance and automated highway systems. For such applications requiring less than one meter of accuracy, the use of other local measurement instruments or differential GPS is essential. However, the use of off-the-shelf devices is still warranted for less mission critical applications such as in-vehicle navigation systems.

The commonly held belief is that GPS is accurate to ± X meters, where X is often viewed as acceptable for the purpose of the system under consideration. This is generally true for stationary applications [9–12] and mobile applications that do not require knowing precisely *when* the mobile device was at the reported

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[0] The data used in this paper is available on the author's website at http://www.cs.uwaterloo.ca/~dthadaller/ and will be made available through CRAWDAD once the work is published.

location. However, in this paper we dig deeper into the effect of mobility on the accuracy of GPS over time and have discovered that position error can be much more significant than we expected.

The research contributions of this paper are:

- We analyze the largely unexplored effects of mobility on the accuracy of off-the-shelf GPS devices. We find that GPS position measurements are delayed by 1.36 seconds, enough time to travel 39 meters at 100 km/h and transmit thousands of packets in a mobile WiFi environment.
- We quantify the amount of systematic and random error and find that systematic error accounts for over 90% of measurement error while moving at 100 km/h.
- We propose simple, yet effective, techniques for significantly reducing systematic position error due to mobility, resulting in a reduction in error of up to an order of magnitude at highway speeds.

2 Background

The Global Positioning System (GPS) is a U.S.-operated system for determining terrestrial position using signals from satellites. The 31 GPS satellites follow a Medium Earth Orbit at 20,200 km above the Earth and orbit the planet twice each day, traveling at over 14,000 km/h [13]. Satellites each transmit a unique repeating code over the 1.5 GHz carrier along with their position. These signals are used by a GPS receiver to determine precise distance to each satellite. Using trilateration, signals from at least three different satellites are used to determine a 2D position fix (four satellites are needed for a 3D fix).

The position measured by the receiver is subject to error from many sources [14]. Because the atmosphere is not a vacuum, effects of the dense ionosphere introduce non-uniform delay in the signal sent from the satellite. In addition, because satellites drift slightly off course, their reported positions can be inaccurate enough to cause measurement errors on the ground. Multi-path and shadowing effects as well as imprecision in the receiver's oscillator can also reduce accuracy.

3 Related Work

Improving GPS accuracy has been well studied. Ehsani et al. [15] explore how less than three meters of accuracy can be achieved using differential techniques that use additional signals sent from known ground stations. Centimeter accuracy can be achieved using Carrier-Phase GPS (CPGPS) and was used by O'Connor et al. [3] to automatically steer farm vehicles. Accuracy can also be improved using additional instruments such as fibre-optic gyroscopes [16, 17]. Furthermore, inertial modeling and Kalman filters can be used to predict device position during GPS outages [16]. The majority of this related work focuses on augmenting the GPS system with additional hardware to achieve accuracy below three meters, whereas in this paper we propose simple software techniques to mitigate systematic errors caused by mobility in off-the-shelf devices.

Fig. 1. Stationary Experiments.

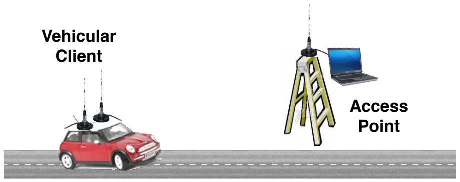


Fig. 2. Mobile Experiments.

Quantifying GPS error has also been studied. Wing et al. [9] found stationary accuracy of commodity devices to be within 5 m to 10 m of true position depending on the view of the sky. Webster et al. [10] found 3-6% error in measuring the size of a 500 m field. A study by the U.S. National Geodetic Survey [11] found 95% of GPS measurements fell within a radius of 6.3 m. Additionally, the manufacturer of the devices we used for this work claims a 10 m position accuracy [12]. Although GPS accuracy has been examined by other researchers, none have examined the effects of mobility as we do in this paper.

In past work [6], we used the techniques described in this paper to perform detailed analysis of wireless protocol operation. In particular, we examined TCP and 802.11 MAC behavior in a drive-by scenario involving a vehicle passing a roadside 802.11 access point at highway speeds. Although our previous work makes reference to the techniques described in this paper, the details and depth of analysis in this paper have yet to be published.

4 Experimental Setup

Equipment: We used the off-the-shelf GlobalSat BU-353 GPS receiver, based on the common SiRF Star III chipset, with a retail price of approximately $100 USD, shown in Figure 1. The device has a USB interface and magnetic mount. It uses standard civilian GPS signals, it does not interpret military signals or use differential GPS.

Mobile Experiments: Mobile GPS experiments were performed in conjunction with 802.11 WiFi experiments described in [6]. In these experiments, a vehicle equipped with an 802.11-equipped laptop drove past a stationary roadside access point mounted on a ladder, as depicted in Figure 2. Both the vehicle and the access point were equipped with GPS devices. We studied the behavior of TCP and MAC layer protocols during different phases of the connection. With a range of only 600 m, it was essential to accurately determine the location where each frame was transmitted on the roadway, relative to the position of the access point. For further details see [6].

Stationary Experiments: To measure consistency between GPS devices, we mounted four identical devices within 10 cm of each other, as shown in Figure 1. The devices were magnetically mounted on a metal sewer grate in the middle of the University of Waterloo campus. The experiments were performed on a day with no clouds, and all devices had a clear view of the sky.

Table 1. GPS Error at 100 km/h

Error	**Impact**	**Mitigating the Error**	**Section**	**Figure**
Infrequent Measurements	6.9 m ± 0.8 m (95% CI)	Systematic error; used linear interpolation between measurements.	Sec. 5.1	Fig. 3
Measurement Delay	37.8 m ± 1.7 m (95% CI)	Systematic error; subtracted 1.36 s from measurement timestamp.	Sec. 5.1	Fig. 4, 5
Single-Device Variation	$\leq$ 4.3 m in 95% of measurements.	Random error; averaged stationary measurements.	Sec. 5.2	Fig. 6
Device Consistency	Captured by above.	Random error; cannot be corrected.	Sec. 5.2	Fig. 7, 8

5 Experimental Findings

Table 1 summarizes the sources of GPS error we identified. We next discuss systematic error, followed by random error.

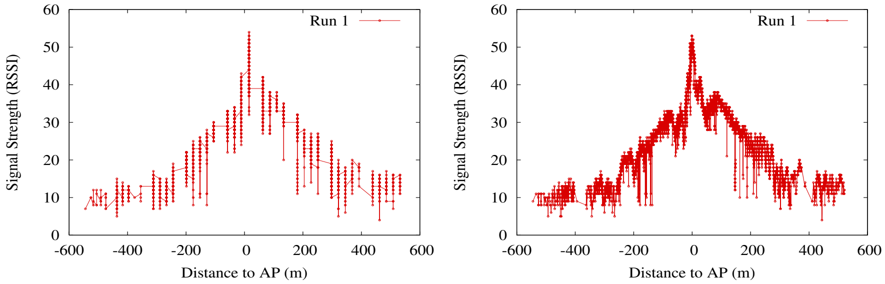
5.1 Systematic Error

Infrequent Measurements Our off-the-shelf GPS receiver only reported position measurements once per second. This is problematic when trying to determine precise position over short time periods.

In our mobile experiments there were thousands of frames transmitted per second. Directly using the GPS measurements resulted in a sparse signal strength map, shown in Figure 3(a). Neglecting to interpolate between measurements results in an average error of 6.9 m ± 0.8 m (95% CI) at 100 km/h.

The frequency of measurements is limited by the NMEA protocol used by the GPS device to communication with the host laptop [18]. The 4800 baud rate specified by the standard allows at most 480 characters per second. With NMEA sentences as long as 82 characters and containing more than just position measurements, it is easy to overrun the communication capabilities [18].

Correcting for Infrequent Measurements: We performed linear interpolation between measurements. A linear fit was appropriate because we were traveling



(a) Raw Measurements (b) Interpolated Measurements

Fig. 3. Using the once-per-second position measurements from GPS results in a sparse signal strength map and an average error of 6.9 m ± 0.8 m (95% CI) at 100 km/h. Performing simple linear interpolation between position measurements improves accuracy and smooths the map.

at a constant speed and did not change direction. In situations where the mobile device changes speed and/or direction, a more complex interpolation would need to be performed. Figure 3(b) shows that using interpolation results in a much smoother signal strength map and more accurate frame locations.

Measurement Delay Knowing precisely when a particular measurement was taken is important for studying precise wireless protocol operation in mobile environments. However, we found that when a position was received on the USB port it was really the position of the vehicle 1.36 seconds in the past. Thus, at 100 km/h, the vehicle was 37.6 m ahead of the reported position at any point in time.

Determining GPS Measurement Delay: We were able to determine the actual position of the vehicle relative to the access point based on the measured signal strength of the wireless signal. The strength of a signal received by a wireless device is proportional to the inverse of the distance to the sender [19]. Therefore, the signal strength will be at its maximum when the vehicle is closest to the access point. Our signal strength measurements exhibited a sharp peak, lasting an average of only 62 ms ± 28 ms (95% CI) (1.7 m at 100 km/h), as can be seen in Figure 3(b). It is therefore reasonable to assume that the peak of signal strength is the position where the vehicle was closest to the access point. With this point of reference, we can determine the GPS measurement error as follows.

Figure 4(a) shows the position of the GPS measurement before the access point (x_{gps1}), at the access point (x_{ap}), at the signal peak (x_{peak}), and the GPS measurement after the access point (x_{gps2}). Recall that the GPS device only reports measurements once per second, thus interpolation is needed. After a GPS measurement is taken, it is reported by the device and read by the host system on the USB port, this takes Δ_{gps}^{read} time. The time to attach a timestamp and log this measurement is Δ_{gps}^{write}. Similarly, the time to read a signal measurement is Δ_{peak}^{read} and to log it takes Δ_{peak}^{write}. The access point's position is known as it has its own GPS device[1].

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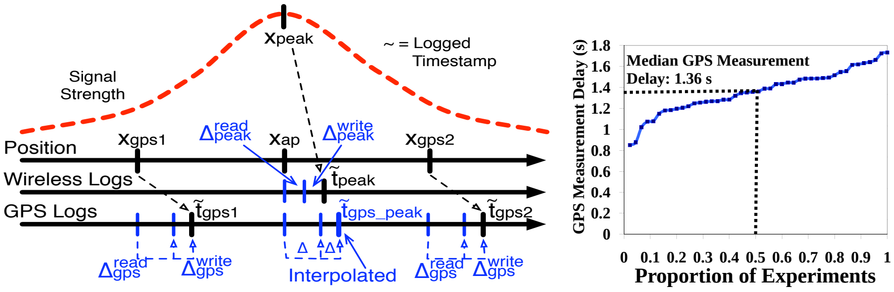
[1] Due to stationary variation, we averaged the measured positions of the access point.



(a) Problem Formulation (b) Empirical Measurements

Fig. 4. Figure A formulates the problem of determining GPS measurement delay Δ_{gps}^{read}. Figure B shows the CDF of Δ_{gps}^{read}, calculated from 45 mobile experiments.

The signal peak is assumed to occur when the vehicle is closest to the access point ($x_{ap} = x_{peak}$). Therefore, the GPS measurement delay is the difference between the time that the vehicle was measured to be closest to the access point ($\widetilde{t}_{gps\_peak}$: requires interpolation) and the time that the signal peak actually occurred ($\widetilde{t}_{peak} - \Delta^{read}_{peak} - \Delta^{write}_{peak}$), as follows:

We first determine the interpolated GPS timestamp at x_{peak}:

$$\text{Define } \widetilde{t}_{gps\_peak} = \widetilde{t}_{gps1} + \frac{x_{peak} - x_{gps1}}{\text{velocity}}$$

Because $\widetilde{t}_{peak}$ and $\widetilde{t}_{gps\_peak}$ are both relative to x_{peak}:

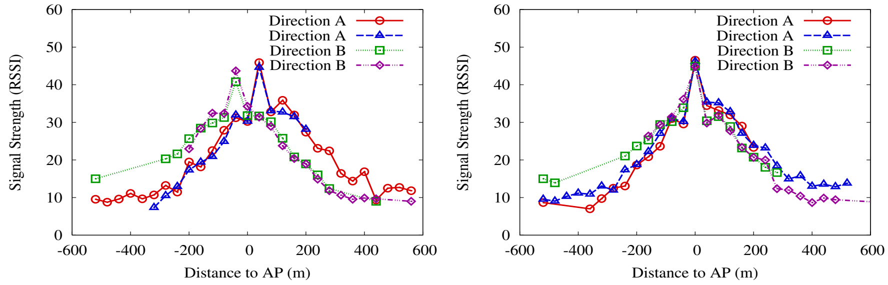
$$\begin{aligned} \widetilde{t}_{gps\_peak} - \Delta^{read}_{gps} - \Delta^{write}_{gps} &= \widetilde{t}_{peak} - \Delta^{read}_{peak} - \Delta^{write}_{peak} \\ \Delta^{read}_{gps} &= \widetilde{t}_{gps\_peak} - \widetilde{t}_{peak} + \Delta^{read}_{peak} + \Delta^{write}_{peak} - \Delta^{write}_{gps} \end{aligned}$$

We make two assumptions only to isolate GPS delay, these do not affect the amount of error experienced: (a) the time to log a GPS measurement and log a signal strength measurement are, for practical purposes, identical ($\Delta^{write}_{gps} = \Delta^{write}_{peak}$), and (b) the time to report a signal strength measurement is negligible ($\Delta^{read}_{peak} = 0$), yielding a best case for Δ^{read}_{gps}:

$$\text{GPS measurement delay } \Delta^{read}_{gps} = \widetilde{t}_{gps\_peak} - \widetilde{t}_{peak} \tag{1}$$

We calculated the GPS measurement delay using Equation 1 from logs of 45 mobile experiments. Figure 4(b) shows a CDF of Δ^{read}_{gps}; the average delay was 1.36 s ± 0.06 s (95% CI).

The cause of GPS measurement error is two-fold. As mentioned earlier, the GPS device communicates with the host laptop at 4800 bps, as specified by the standard NMEA protocol. Because of this low baud rate, some devices elect to, or are forced to, send data that is slightly out of date [18]. Second, there is an inherent delay in computing a GPS position, as signals from each satellite



(a) Before Correction (b) After Correction

Fig. 5. Validation of computed measurement delay; subtracting 1.36 s from the GPS timestamp corrects for GPS measurement delay. Two runs in each direction are shown, Figure A shows the difference in measured signal peaks before correction; Figure B shows that after correcting for this systematic error, the signal peaks align.

must be measured sequentially. Therefore, when a computation is completed, the measurement is already out-of-date.

Correcting for Measurement Delay: Subtracting 1.36 s from the timestamp reported by each GPS measurement was adequate to correct for GPS measurement delay in our experiments. We caution the reader that other devices may experience different delay, and the measurement delay should be determined before applying any correction. However, we expect that the majority of off-the-shelf devices will experience similar delay as it is inherent to the operation of standard NMEA GPS devices.

Validation of Correction for Measurement Delay: We validate our correction by comparing experimental runs done with the vehicle traveling in the both directions on the road. Before correction, the signal peaks do not align (Figure 5(a)), and after applying our correction, the signal peaks align (Figure 5(b)). Therefore, our correction reduces error due to measurement delay.

5.2 Random Error

Single-Device Variation Over a 5.5 hour period, the measured position of the stationary access point varied by as much as 10 m. Figure 6 shows the 95% support of the distribution of measurements, along with the mean, median, and mode. Based on the support, 95% of measurements are within a box of size 4.6 m × 5.7 m. Although we did not know the true location of the access point, the average of all stationary measurements is a reasonable approximation. Therefore, the error in 95% of measurements will be no more than 4.3 m, the distance from the average to the furthest corner of the support box.

Reducing Impact of Single-Device Variation: Measurements can be averaged to reduce error due to stationary variation.

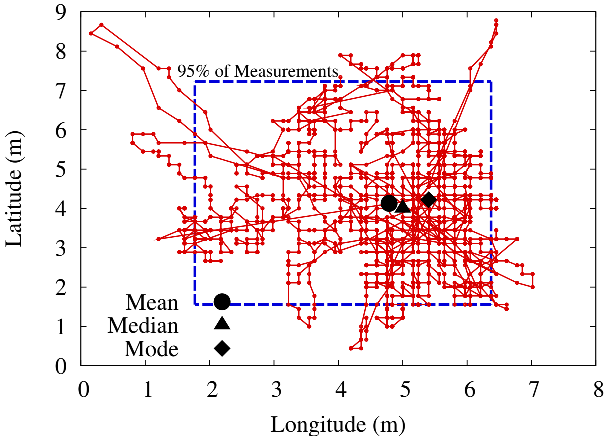


Fig. 6. The measured position of the stationary access point over a 5.5 hour period.

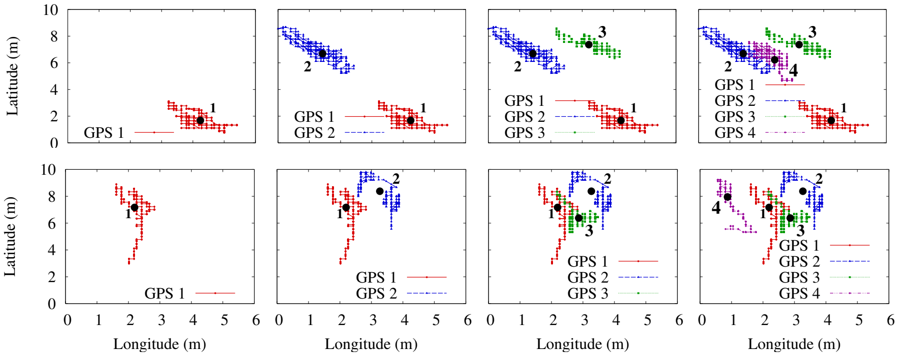


Fig. 7. Top 4: Measurements from four nearby GPS devices over 30 minutes. Bottom 4: The same four devices 10 minutes later. Average measured location is shown for each device.

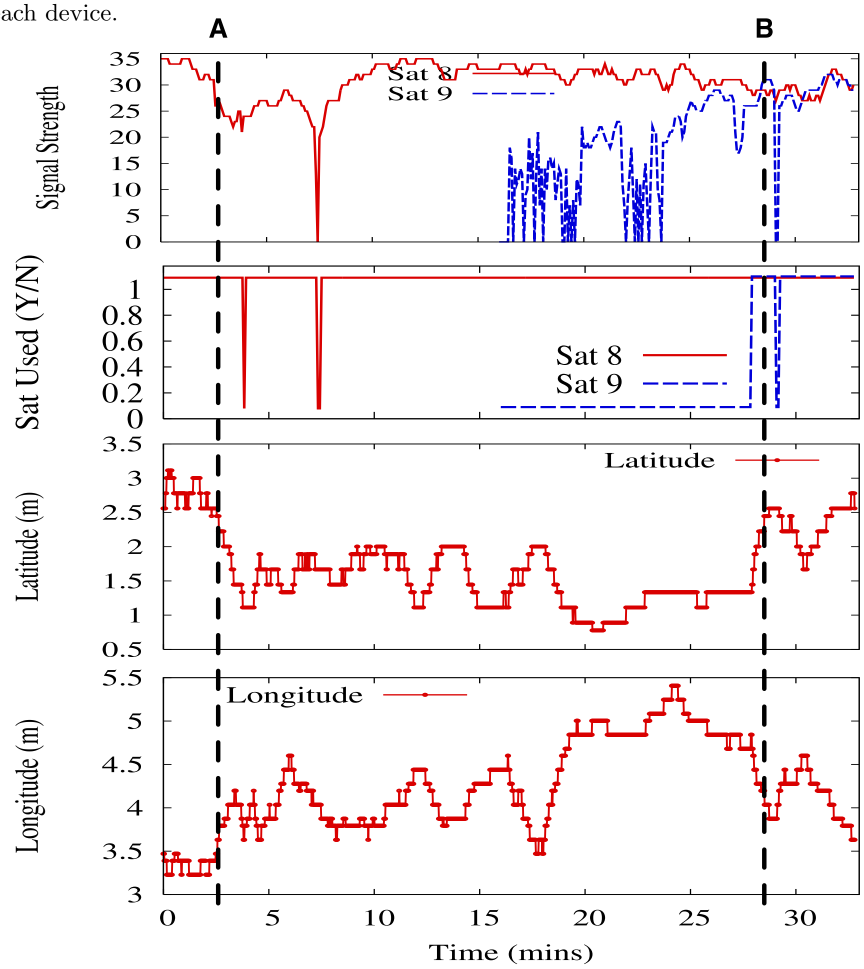


Fig. 8. The effects of satellite selection over 30 minutes for a stationary device (GPS1, shown in the top left of Figure 7). At point A, Sat 8 was temporarily removed due to its weaker signal strength; at point B, Sat 9 was added. These changes affected both the latitude and longitude.

Consistency Between Devices To investigate device-specific measurement bias, we placed four identical GPS devices within 10 cm of each other as shown earlier in Figure 1. Upon first inspection some measurement bias appeared, as shown in the top half of Figure 7, showing 1800 measurements per device collected over a 30 minute period. However, 10 minutes later, measured positions from the devices all crossed over, shown in the bottom half of Figure 7. This indicates there is no prominent device-specific bias for our hardware.

However, at any point in time, there was up to 10 m difference between measurements from the four devices. Further analysis revealed that this inconsistency was primarily due to satellite selection done independently at each device.

Understanding Satellite Selection: During the 30 minute period shown in the top half of Figure 7, 15 satellites were detected by each receiver, eight were used the entire time, four were never used, and three were only used part of the time. Each of the four devices selected a different subset of these three satellites at different times, leading to the reported position differences. To better understand the effects of satellite selection, Figure 8 shows satellite choices for a single stationary device (GPS1 from the top of Figure 7).

We draw two conclusions from these measurements: (1) The strength of the signal received from a satellite determines whether the GPS receiver will use that satellite in the position calculation, and (2) changing which satellites are included in the calculation affects the measured position. Although satellite selection is only one of many causes of stationary error, it is important to understand its impact on measured position.

Reducing Inconsistency: There is no way to reduce this error as the selection of satellites cannot be controlled.

6 Discussion and Recommendations

We have presented results showing GPS error of 4.3 m while stationary and 44.7 m while moving at 100 km/h. We have demonstrated how simple, yet effective, techniques can be used to significantly reduce systematic error due to mobility. Our recommendations are as follows:

- Use linear interpolation to fill in the gaps between the once-per-second GPS measurements.
- Subtract the appropriate delay from the timestamp of position measurements to correct for the delay in reporting measurements.
- When stationary, average position measurements over time to mitigate the effects of single-device variation.

Although we have identified some significant sources of GPS error, we caution the reader that GPS devices made by other manufacturers may exhibit different, and possibly more, error. However, the fundamental sources of error remain unchanged: the 4800 baud rate specified in the NMEA standard limits the frequency of position reports, and calculating position from GPS satellites is inherently lengthy due to the need to sequentially measure distance from each satellite.

7 Conclusion and Future Work

We find that mobility causes a significant amount of error in off-the-shelf GPS devices. We measured error in a highway scenario and found average position inaccuracies of 49.0 m at 100 km/h. We demonstrated that mobility causes over 90% of this error, due to the infrequency that the GPS device reports measurements (once per second) and 1.36 seconds of delay between when the position is calculated and when it is reported. Because this mobility error is systematic, we were able to significantly reduce it using linear interpolation and adjusting the GPS timestamp to correct for delay. This resulted in up to an order of magnitude reduction in GPS error while mobile.

As future work we plan to broaden our study to include devices from other manufacturers and other mobility scenarios, such as urban environments.

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