Real-time averaging of position data from multiple GPS receivers

Daniel K. Schrader[a], Byung-Cheol Min[a,*], Eric T. Matson[a], J. Eric Dietz[a,b]

[a] *Department of Computer and Information Technology, Purdue University, West Lafayette, IN, USA 47907*
[b] *Purdue Homeland Security Institute, Purdue University, West Lafayette, IN, USA 47907*

Abstract

Making GPS more accurate and/or reliable by combining it with other sensors and applying sophisticated data processing techniques has been attempted many times. Our approach to enhancing the performance of GPS is much simpler than most. We combine multiple (up to eight) consumer-grade GPS receivers into a system that averages their data in real time, requiring no other sensors, augmentation technologies, or powerful processors. The results show significant improvement in both accuracy and reliability of the data over that of a single receiver, and the distribution of error more closely resembles the normal distribution (as compared to a single receiver). Our multi-GPS system shows potential to be an inexpensive way to achieve better GPS performance with only "off-the-shelf" equipment.

Keywords: multi-GPS system, data fusion, averaging, inexpensive

1. Introduction

Localization is important in many applications, such as robotics, aviation, search and rescue, agriculture, and anything that requires navigation [1, 2, 3, 4, 5]. GPS (Global Positioning System) is a common method of localization, partly due to its relative ease of use, but also because it is an inexpensive way to obtain an absolute position (with respect to the Earth). GPS equipment comes in all shapes and sizes, from sub-$100 consumer-grade receivers to military- or professional-grade equipment that can cost thousands or tens of thousands of dollars [6]. This difference in price comes with many differences in performance, the most notable of which is accuracy. For example, consumers can expect position accuracy on the order of 10 meters for well under $100 [7]. However, obtaining centimeter-scale accuracy requires equipment closer to the other end of the price spectrum, like the John Deere StarFire 3000 GPS receiver (with the RTK radio) [8].

More accurate localization is better localization, but it is not always possible to obtain high-end GPS equipment. The objective of this research is to create an inexpensive GPS module that outperforms consumer-grade receivers (in accuracy and/or reliability), but does not use any additional sensors or sophisticated processing, since these would add to the cost. Towards this goal, we combined eight sub-$100 GPS receivers into a system that averages their data in real time. The system's output has a very similar syntax to that of the individual GPS receivers, which was done intentionally, to enable our system to be "hot-swappable" with common GPS receivers.

*Corresponding author

Email addresses: dkschrad@purdue.edu (Daniel K. Schrader), minb@purdue.edu (Byung-Cheol Min), ematson@purdue.edu (Eric T. Matson), jedeitz@purdue.edu (J. Eric Dietz)

2. Related Works

Making GPS more accurate by augmenting it with corrections or additional sensors has been attempted many times, with varying levels of success. Godha and Cannon saw accuracy down to one meter or below, but they used a very expensive IMU (Inertial Measurement Unit) to achieve these results [9]. Matosevic et al. constructed a system that is somewhat analogous to DGPS (Differential Global Positioning System), which gave them an improvement in accuracy of almost 80% [10]. Diving fully into the realm of sophisticated sensor fusion, Grejner-Brzezinska et al. combined DGPS, IMS (Inertial Measurement System), pseudolites [11], and laser scanners in what they called "tight quadruple integration" [12]. These studies are just a few examples of what many have tried, and they serve as a representative sample of methods that the authors of this article intentionally stayed away from (see the Methodology section). On the other end of the scale, Trinklein and Parker developed a GPS solution that resembles the methodology described in the Methodology section below, by combining inexpensive GPS receivers into groups to enhance accuracy [13]. The functional difference between the work presented in this paper and that in [13] is that Trinklein and Parker's groups of GPS receivers were used to calculate relative distance in a mobile application, rather than a stationary position. Trinklein and Parker also employed post-processing of the GPS data, as opposed to the real-time data processing used in this experiment (see section 3.2).

Attempting to improve the accuracy and/or reliability of GPS receivers is not a new idea, as these related works demonstrate, but the novelty of the work presented in this paper is its minimalism. No other sensors were used, and a maximum of $30 USD in processing power was all that was needed (not including the computer that simply recorded the output). In addition to its simplicity, the system described in this paper is interchangeable with any GPS receiver that outputs the standard

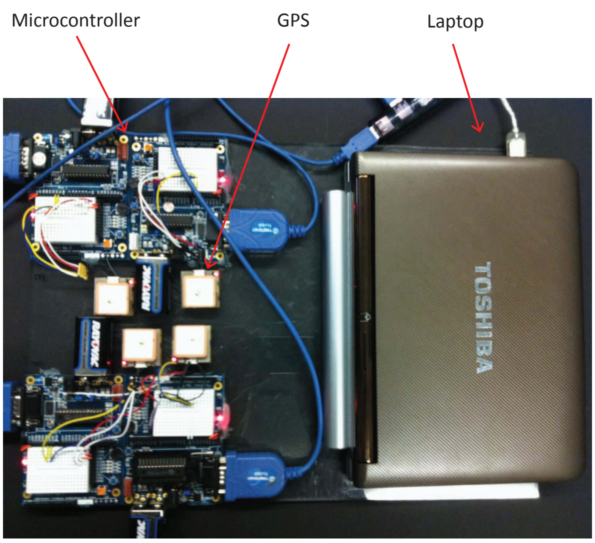


Figure 1: System used to collect data for the proof of concept, desribed in [14].

NMEA 0183 message.

3. Authors' Previous Work

3.1. Proof of Concept

The first step in developing our multi-GPS device was to show that the concept of averaging the GPS receivers' data is effective enough to move forward. As described in our first publication on this subject [14], testing the averaging concept was done by recording data from four GPS receivers (shown in Figure 1), then using commercial PC software to analyze the data. The use of PC software is significant because it means the calculations were done with a 32-bit, floating point system (as opposed to the next iteration of the multi-GPS system [15], described below). To obtain the results, we used three simple formulas as follows:

$$x_{avg} = \frac{\sum_{i=1}^{n} C_{lat_i}}{n} \tag{1}$$

$$y_{avg} = \frac{\sum_{i=1}^{n} C_{lon_i}}{n} \tag{2}$$

where C_{lat_i} and C_{lon_i} are the latitudinal and longitudinal distances to the reference point of the i-th GPS receiver, and n is the number of GPS receivers. Using the results of (1) and (2), a distance D from the reference point is calculated by

$$D = \sqrt{x_{avg}^2 + y_{avg}^2}. \tag{3}$$

Our reference point was a National Geodetic Survey control point, designated NGS Q 94. The coordinates of NGS Q 94 are known to much greater precision and accuracy than is attainable from the GPS receivers used to collect this data, so it serves as a useful point of comparison. The algorithm used to convert the "raw" GPS data into arithmetically-useful numbers

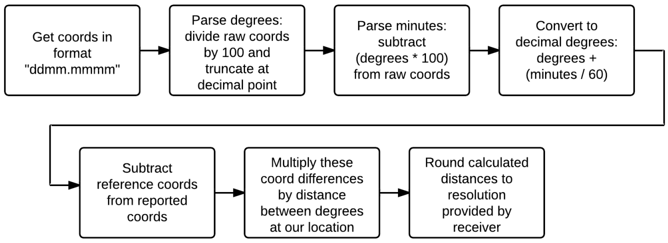


Figure 2: Process used to convert GPS coordinates to a distance from the reference point (NGS Q 94) [14].

is represented in Figure 2. In this figure, the "ddmm.mmmm" in the first step refers to the degree/minute data format that is provided by the EM-406A receivers.

The results of the proof-of-concept experiment are summarized in Table 1 and Figures 3 - 5. The different time intervals were intended to emulate larger numbers of GPS receivers, by considering the data in terms of the number of coordinate pairs. For example, collecting data from 4 GPS receivers for 15 seconds produces the same number of coordinate pairs as 10 GPS receivers for 6 seconds. For this test, The equations (1) to (3) are no need to change, but parameters n and i then represent the number of collected coordinate pairs and the i-th latitudinal and longitudinal distances, respectively. While not a perfect emulation, it produced results that were interesting enough to move forward with the research.

3.2. Stand-alone Multi-GPS system

After demonstrating the validity of our concept for a multi-GPS system, the next step was to develop a stand-alone device with the capability to combine (average) data from multiple GPS receivers in real time. Eliminating the need for post-processing of the GPS data, using only very inexpensive hardware, proved to be a complex enough task that it became the foundation of a Master's thesis [15]. The idea and the overall process remained the same, but the execution of that process changed significantly. Instead of sending GPS data directly to a computer to be recorded, each GPS receiver sent it's data to a low-power, 8-bit microcontroller. The microcontrollers parsed and processed the data in real time, producing a new GPS sentence that represented the fusion of all the receivers' data.

Two arrangements - centralized and decentralized (Figures 6 and 7, respectively) - were built and tested. The centralized system was composed of two slaves, each with four GPS receivers connected, and a master. The additional step of using slaves between the master and the GPS receivers was necessary, due to resource limitations on the microcontrollers. The decentralized system did not have the same resource limitations, in terms of the microcontrollers, since it operated in a linear fashion, with each microcontroller only communicating with its immediate neighbors. Figure 8 shows the decentralized system in action.

Testing two different system architectures was done to determine if either possessed superior performance or otherwise notable traits. A summary of the results from both systems is presented in Tables 2 and 3. The full study (see [15]) contains more data, such as what happened after applying a simple filter,

# GPS	Distance from Reference Point (m) First Trial				Second Trial				Third Trial			
	1sec	15sec	1min	4min	1sec	15sec	1min	4min	1sec	15sec	1min	4min
1	2.57	3.13	2.99	0.99	6.41	6.59	5.93	3.80	4.12	5.65	5.62	2.67
2	1.88	1.99	2.06	2.17	2.48	2.55	2.41	2.15	2.09	2.48	2.16	1.43
3	0.91	1.07	1.29	1.98	0.63	0.69	0.60	0.42	1.78	1.65	1.24	1.22
4	2.57	2.80	2.38	1.84	1.52	1.34	0.89	1.71	2.38	2.34	2.61	2.53

Table 1: Distances from reference point for all 1 second, 15 second, 1 minute, and 4 minute trials [14].

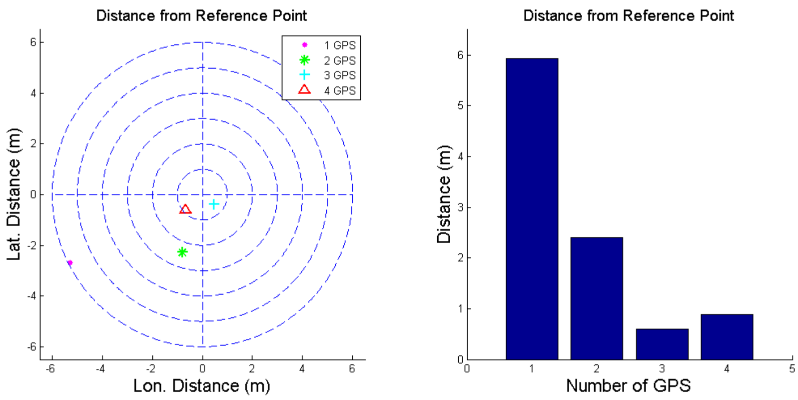


Figure 3: Average errors of GPS coordinates for a 1 minute trial [14].

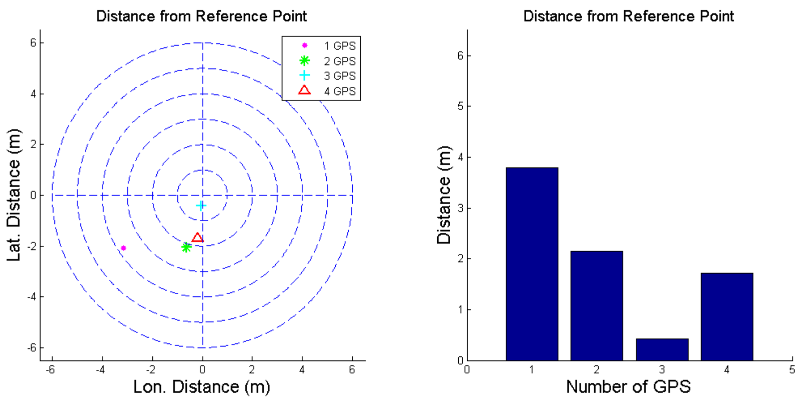


Figure 4: Average errors of GPS coordinates for a 4 minute trial [14].

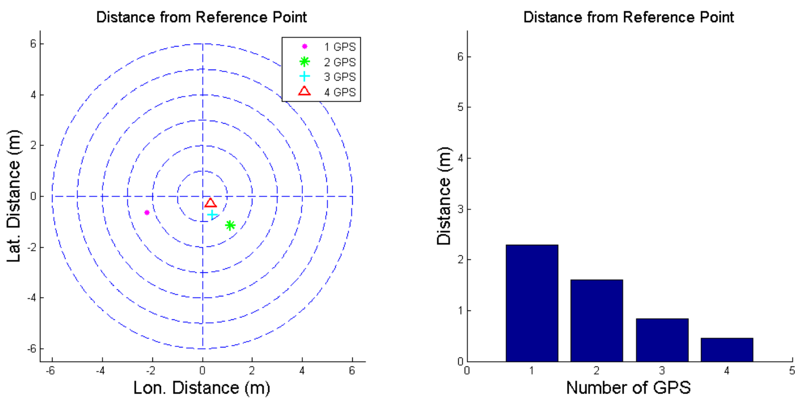


Figure 5: Average errors of GPS coordinates for a 20 minute trial [14].

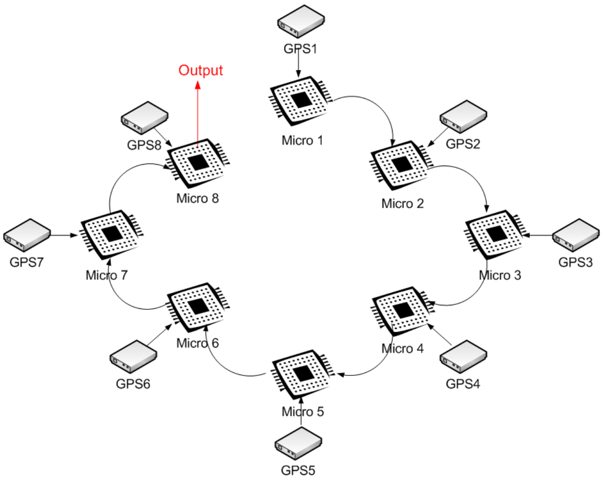


Figure 6: Schematic of the centralized design for the multi-GPS system, shown with 8 GPS receivers [14].

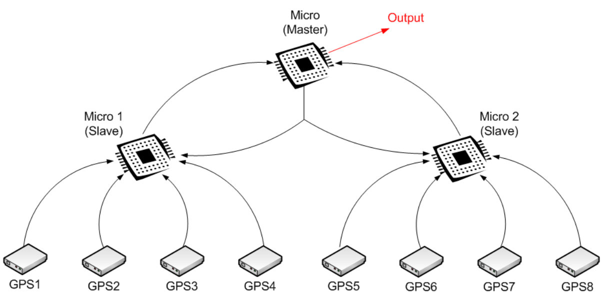


Figure 7: Schematic of the decentralized design for the multi-GPS system, shown with 8 GPS receivers [14].

but the data shown here is a good representation of the experiments.

Although it is likely possible to improve the performance of the systems represented in Tables 2 and 3, we thought time and resources were better spent by developing an improved, simpler multi-GPS system. Doing even relatively simple arithmetic with GPS data is difficult on 8-bit processors that cannot perform floating-point calculations. Our approach to solving this problem was to remove the low-power microcontrollers and give the number-crunching tasks to a much more capable device: a 32-bit processor (with floating-point capability), in the form of a small netbook computer. While the computer is the most expensive component of the new system, with further development, it could be replaced by a much more compact and low-cost (but still powerful, compared to 8-bit processors) processor, such as an ARM device.

4. Methodology for the New Multi-GPS System

The methods and techniques employed for this latest iteration of our multi-GPS system are, in the same spirit as the earlier attempts, relatively simple. Our deliberately simple, inexpensive approach is in contrast to the many complex (and usually expensive) attempts at improving GPS accuracy (see Related Works section). To that end, we used "off-the-shelf" equipment that totaled under $1000, including the netbook computer. Figure 9 shows this collection of parts gathering the data that is presented in the Results and Discussion section of this article.

Algorithm 1: Multi-GPS system in real time

Data: raw GPS data
Result: combined latitude and longitude data
initialization;
while *signal lock on all receivers?* **do**
    $n \longleftarrow$ *status indicator*;
    poll all receivers;
    verify checksums;
    if *checksums is bad* **then**
        $n \longleftarrow (n - \textit{the number of bad GPS receivers})$;
    parse latitude and longitude data, C_{lat} and C_{lon};
    combine data uisng $\frac{\sum_{i=1}^{n} C_{lat_i}}{n}$ and $\frac{\sum_{i=1}^{n} C_{lon_i}}{n}$;
    print out results;

The overview of our multi-GPS system's operation is shown in Figure 10. These steps are carried out in real time by the computer in Figure 9, using a program written in Python.

In Figure 10, the second step, signal lock on all receiver, means all the GPS receivers have locked onto satellites and are outputting coordinate data. The receivers include a status indicator in the string they output. If this indicator is a zero, that means the receiver is not getting data from enough satellites. If the indicator is a 1, 2, or 3, that means the receiver is getting data from enough satellites to be able to determine its coordinates. Therefore, every time the receivers send their string, and our Python code checks that status indicator. Until all receivers show a non-zero status, no data is recorded.

The fourth step, verify checksums, is included to verify chcksums of received GPS data. If the checksum is bad, that particular string is discarded. The other data is not necessarily discarded. For example, if 8 receivers sent data, but 2 checksums were bad, the other 6 receivers' data would still be processed and recorded. The number of good data was recorded each time, so if the above scenario happened, the custom GPS sentence we made would say "6" instead of "8".

The last step, combining the data, consists of some pieces of data being averaged and some minimums being extracted. Latitude, longitude, horizontal dilution of precision, and altitude were averaged. The minimums of the timestamp and the number of satellites in view were recorded, because when combining non-sychronized GPS data into (pseudo) NMEA format, the oldest data with the fewest satellites in view is the least common denominator, so to speak. Implementation of our multi-GPS system in real time for latitude and longitude, which are we are most interested in this research, is algorithmically summarized in Algorithm 1.

Looking at Figure 9, the "nuts and bolts" of the multi-GPS system are visible. On the right side of the image, the ring of GPS receivers can be seen. This arrangement was chosen to cancel out the errors introduced by the receivers not being directly on the measured location. When combining only two

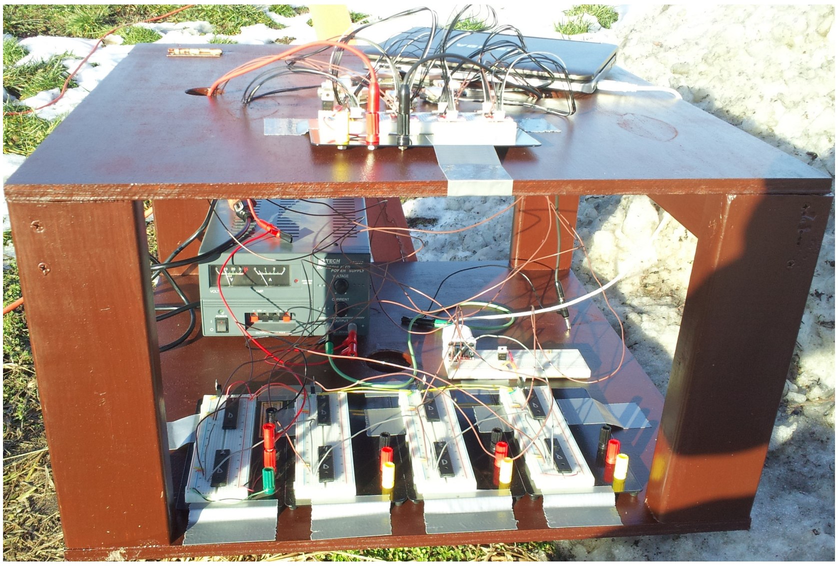


Figure 8: Prototype of the decentralized multi-GPS system [14].

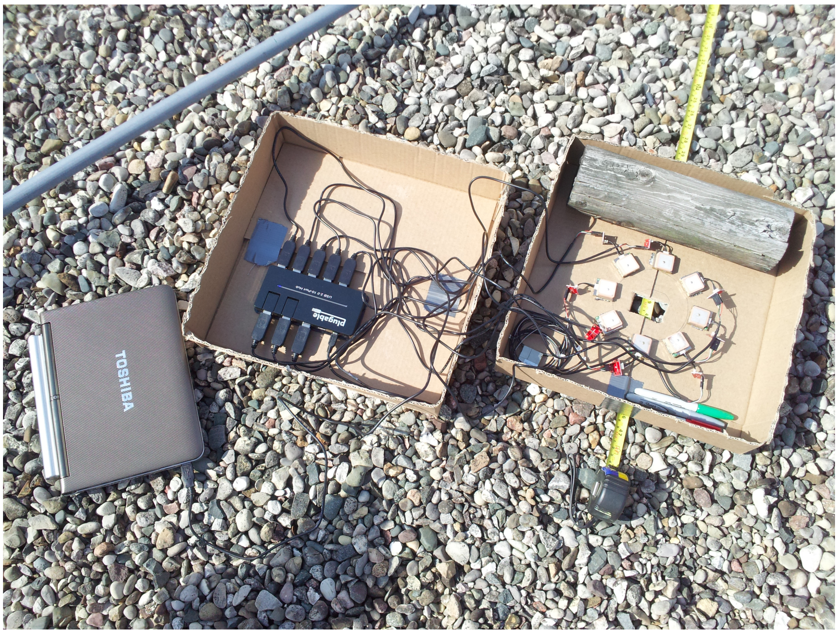


Figure 9: Second-generation prototype of the multi-GPS system; GPS receivers are on the right, computer and supporting hardware are on the left.

or four receivers, receivers opposite each other were selected. In the center of the image is a USB hub with a connection to each GPS receiver, which is then connected to the computer on the left. The measuring tape that runs underneath the ring of GPS receivers ensures that the center of the ring is a known distance away from the reference point, which is the NGS CORS known as "PRDU". Comparing the coordinates reported by the multi-GPS system to those of the reference point allows for an absolute measurement of error.

During the experiment, 6300 data points were collected for each configuration of GPS receivers (two, four, and eight, as well as each individual receiver). Since each receiver sent its data to the computer, as opposed to the data being combined before the computer received it, analysis of the performance of each receiver is possible. This method of data collection also means that, for any given data point, the results for combining different numbers of receivers can be calculated using the same set of GPS data, thus eliminating the factor of differences in environmental conditions.

The description so far does not hide any details of our data fusion technique. No filters or algorithms (beyond simple averaging) are employed. As mentioned in the previous sections, such data processing techniques fall outside of the scope of this study. Our intention was to determine if simply averaging multiple GPS receivers' data would improve the performance of the system, as compared to a single receiver.

# GPS	1			2			4			8		
# coords.	1	10	100	1	10	100	1	10	100	1	10	100
Cen	2.2	2.2	2.2	1.6	1.6	1.4	2.8	2.8	2.8	5.0	5.1	4.6
Decen				2.7	2.7	2.5	6.8	6.7	6.9	2.0	1.9	2.0

Table 2: Median errors of GPS systems in [15] (meters)

# GPS	1			2			4			8		
# coords.	1	10	100	1	10	100	1	10	100	1	10	100
Cen	-	-	-	27	27	36	27	27	27	127	132	109
Decen				23	23	14	209	205	214	9	14	9

Table 3: Percent difference in median errors (compared to 1 GPS receiver) of GPS systems in [15]. Black indicates a decrease in error, red indicates an increase in error.

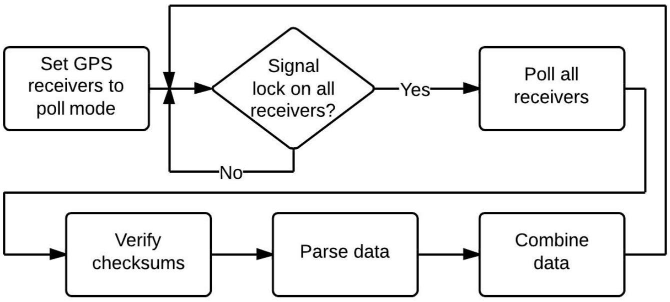


Figure 10: Multi-GPS system flowchart; Overview of the procedure employed by the multi-GPS system.

5. Results

The results of our multi-GPS experiment are fairly straightforward. Figure 11 summarizes the performance of each GPS receiver individually. The purpose of this is to show how much variance there is in "identical" consumer-grade GPS receivers. Figure 12 summarizes the performance of the multi-GPS system in its various configurations of receivers. The single-receiver data in Figure 12 is from receiver G (see Figure 11), which was chosen because it puts the performance of the multi-GPS system into the context of comparison to its worst-performing component (since a user of this model of GPS receiver could not assume better performance from any given receiver, without emperical analysis). Figures 13 and 14 show the histograms for each GPS receiver and for the different configurations of multiple receivers, respectively. Normal curves are overlaid onto the histograms to provide visual comparison to a Gaussian distribution.

In Figure 14, one can notice that variance of average errors consistently could become smaller, as the number of GPS receivers increases. This could be expected with the variances shown in Figure 13 that shows many of errors for each GPS receiver follow Gaussian (Normal) distribution (albeit some do not follow it). Consequently, it was identified that our averaging technique is fairly related to the central limit theorem [16], and therefore variance of average errors could be narrower as the number of GPS receivers increases.

6. Conclusions

GPS is a common tool for localization, but depending on the application, the accuracy that inexpensive, consumer-grade GPS receivers provide may not be sufficient. This lack of accuracy is not a new problem, and many attempts have been made to enhance GPS accuracy by combining different types of sensors and/or applying relatively sophisticated data processing techniques. This study took a different approach by simply averaging the data from up to eight identical, sub-$100 GPS receivers in real time.

Referring to Figures 11 and 13, it is evident that the performance of the GPS receivers used in this study varied significantly from receiver to receiver. The large variance in performance is important, because a user of this particular GPS receiver, which is representative of consumer-grade GPS, may get average accuracies ranging from about two meters to almost ten meters. Even worse, any single datum could yield accuracy as poor as almost 30 meters. With no additional data, there would be no way to know how accurate the reported position is at any given time, which is where the multi-GPS system comes into play.

Figures 12 and 14 quantify and visualize the performance of the multi-GPS system. Just going from one receiver to two, some interesting results emerge. The distributions of error for single receivers are varied and do not always follow the normal curve very closely, but with two receivers, the distribution is noticeably closer to Gaussian (see Figure 14a). The average accuracy is only marginally better, but the maximum error and the standard deviation show significant improvements of 59% and 45%, respectively. With four and eight receivers, all three metrics in Figure 12 show appreciable improvement over one and two receivers. However, the performance gains when going from four to eight receivers are relatively small and would likely not warrant the doubled cost of equipment.

Combining multiple, inexpensive GPS receivers into a system that simply averages their data (or selects particular values) showed significant performance improvements over a single receiver, both in accuracy and reliability. This study went up to eight receivers, which could be increased, but doing so would likely not provide a very compelling price/benefit ratio. Different applications have different performance requirements,

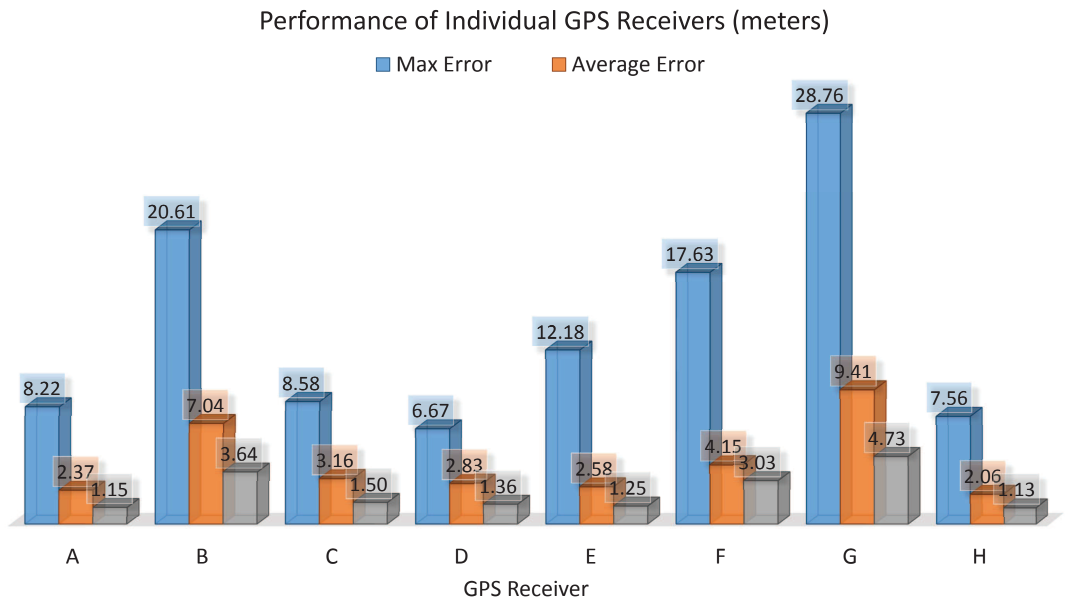


Figure 11: Summary of the results for individual GPS receivers; Blue bars show maximum errors, orange bars show average errors, and grey bars show standard deviations of errors.

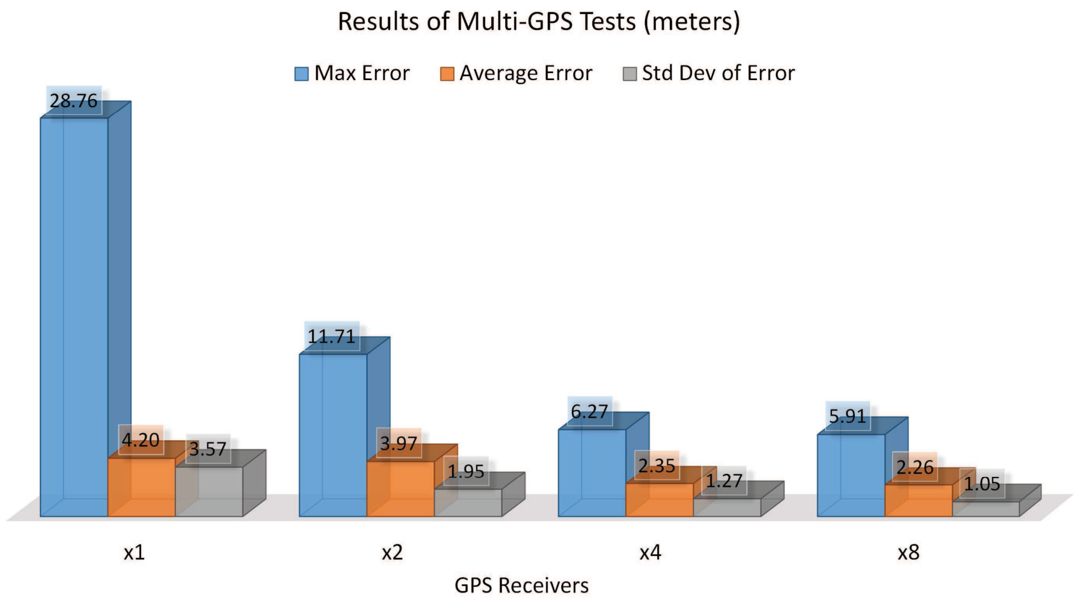
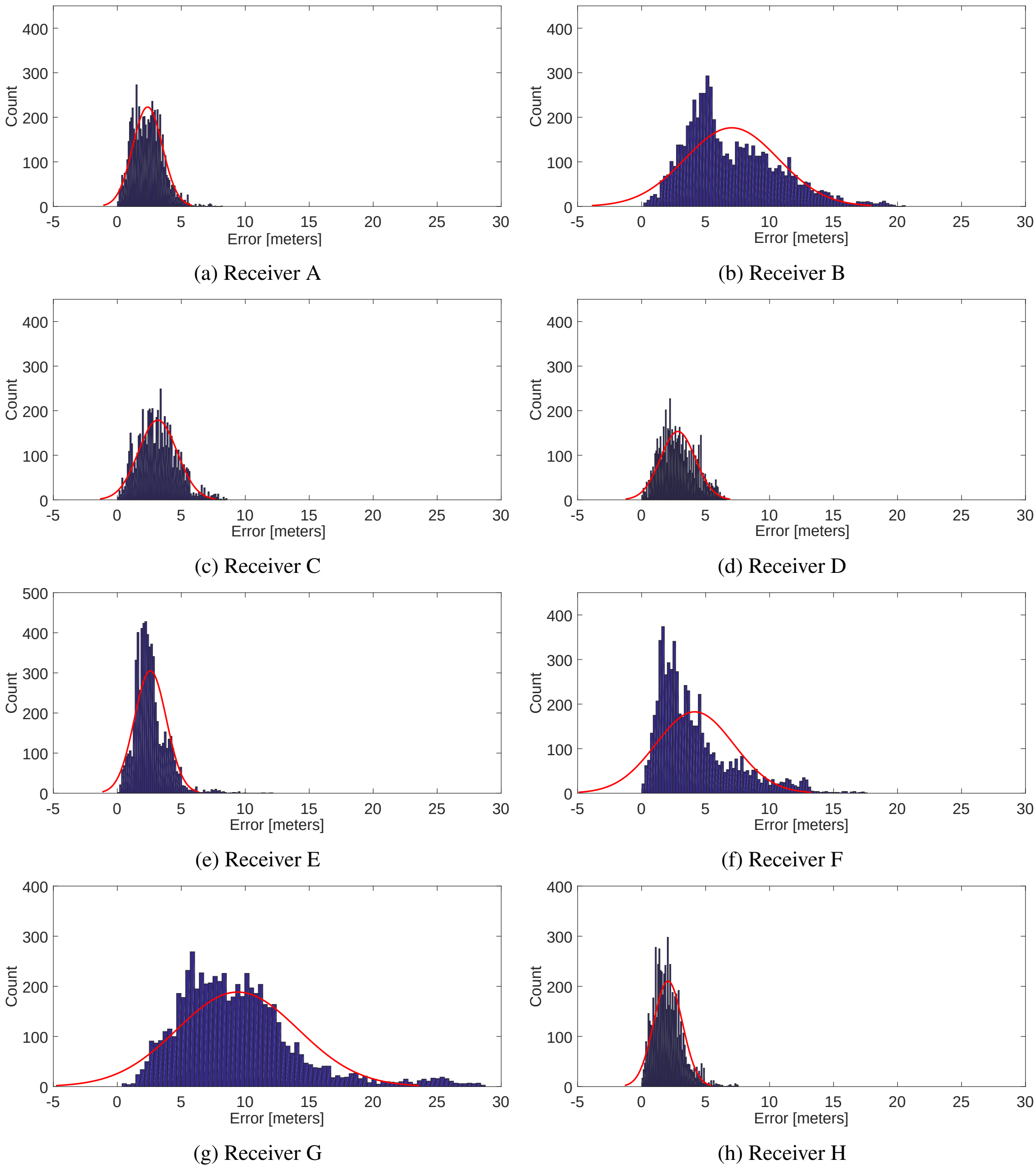
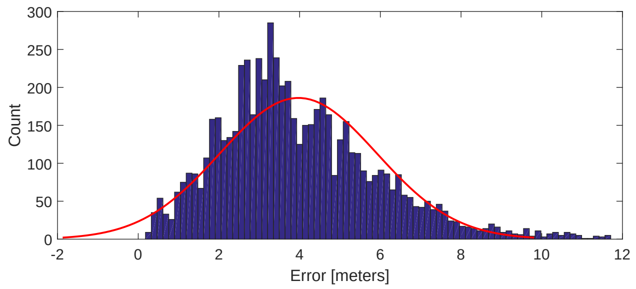


Figure 12: Summary of the results for multi-GPS tests; Blue bars show maximum errors, orange bars show average errors, and grey bars show standard deviations of errors.

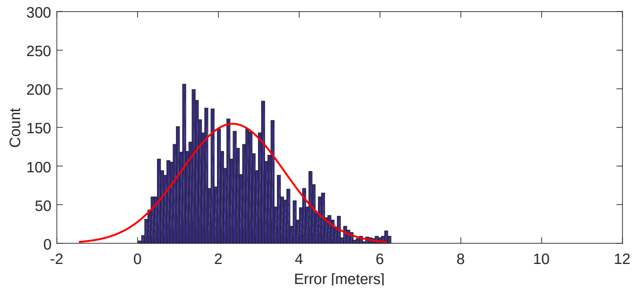


(a) Receiver A (b) Receiver B (c) Receiver C (d) Receiver D (e) Receiver E (f) Receiver F (g) Receiver G (h) Receiver H

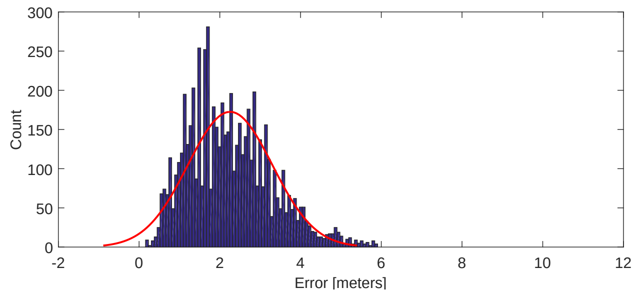
Figure 13: Distributions of error for each GPS receiver; Normal curves are overlaid.



(a) Two receivers



(b) Four receivers



(c) Eight receivers

Figure 14: Distributions of error for different multi-GPS configurations; Normal curves are overlaid.

but based on the available data, a two- or four-receiver system strikes the best balance between cost and performance. With some refinement and miniaturization, a multi-GPS device could be a useful tool for a variety of applications.

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