

NIST Technical Note 1962

**Test & Evaluation of the Safety App
from 911Cellular, LLC at NIST**

Nader Moayeri
Lu Shi
Chang Li

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National Institute of Standards and Technology

Kent Rochford, Acting NIST Director and Under Secretary of Commerce for Standards and Technology

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Executive Summary

At a time when more than 70% of the calls made to 911 are placed from cell phones, it is vital for Public Safety Answering Points (PSAPs) to be able to dispatch emergency responders to the right location for the caller. A major challenge in this area is the location accuracy of E911 calls placed from inside buildings. [According to the Federal Communications Commission \(FCC\)](#)¹, more than 10,000 people, who would otherwise be saved, die every year when calling 911 from a cellphone because emergency dispatchers can't get a quick and accurate location on them. The latest rules from the FCC require 50-meter horizontal location accuracy or providing dispatchable location for 80% of E911 calls by April 2021. As for vertical accuracy, the FCC has called for one or more vertical (z-axis) location accuracy metrics to be defined by nationwide providers and certain benchmarks, yet to be defined, based on those metrics to be met by certain dates.

The Safety App from 911Cellular, LLC is a Wi-Fi-based app for placing E911 calls. In December 2016, NIST tested and evaluated the Safety App in a comprehensive manner according to the procedures of the international standard ISO/IEC 18305, Test and evaluation of localization and tracking systems, in a large, four-story building on the NIST campus in Gaithersburg, Maryland. The Safety App achieved an average horizontal accuracy of 7.45 meters, it had a horizontal accuracy of 15.11 meters or better in 95% of the area of the building, and correctly decided from which floor the E911 call was placed in 87.6% of the area of the building. These results for a technology that is available today are far better than what FCC rules have called for by 2021. However, to achieve this level of accuracy *everywhere* (i.e., in every building), there has to be good Wi-Fi coverage and access to the Internet *everywhere*. The key questions are (i) what the penetration rate of Wi-Fi is now and (ii) what it will be by 2021. One clear trend is that Wi-Fi is being deployed in more buildings every day. When Wi-Fi access to the Internet is not available, the Safety App falls back to the use of GPS and RF signals received by the cellular base stations from the cell phone, which are the traditional solutions to estimate the location of E911 calls. Therefore, one point that can be made is that Wi-Fi-based E911 solutions should be used along with the traditional solutions to improve the indoor location accuracy of E911 calls, just as the 911Cellular Safety App does.

The Safety App has a very simple operation and its performance does not degrade in high rise buildings. Even though NIST tested the Safety App in a four-story building, the App's performance would be just as good in a 100-story building, as long as the Wi-Fi coverage on all floors of the building are the same. Nevertheless, it is important to test the Safety App in a few other buildings to study the effects of various construction materials, layout, etc.

This report presents in detail the testing methodology and test results that were obtained.

¹ <https://www.documentcloud.org/documents/2195636-fcc-third-nprm-february-2014.html#document/p15>

I. Introduction

[The Safety App from 911Cellular, LLC](https://www.911cellular.com/)² is a smartphone app that allows a person to make an E911 phone call from his/her smartphone at the time of an emergency. Just like any 911 call made from landline phones, the call could be due to the person having a serious medical emergency and needing immediate attention or a situation in which the person's physical safety is at risk. Such calls are routed to PSAPs, whether they originated from landline or mobile phones. The PSAP would then dispatch emergency responders to attend to the person under distress. To do this, the PSAP needs to know the location of the person needing help. This is straightforward in the case of a 911 call made from a landline phone, because the address where the phone is located can be found in the telephone company database. The problem is much harder when the 911 call is made from a mobile phone, because the mobile phone is not tied to a particular location and it can be anywhere. This is called E911.

Presently, there are two main techniques for determining the location of an E911 call. One is triangulation based on the properties of the radio frequency (RF) signals received from the mobile phone at various cellular base stations that can hear the mobile phone. The properties of interest are the strength of the signal, the time of flight of the signal from the mobile phone to a base station, or the direction of arrival of the signal at the base station. A wide range of numbers have been reported for the accuracy of location determination based on signals received at base stations that could be away from a mobile phone on the order of kilometers. One paper³ reports that the accuracy is from 200-300 meters. Another one⁴ reports an accuracy range of 50-200 meters. It has been stated in an [FCC report](#)⁵ (see Clause 84 in Page 33) that "While Qualcomm states that initial field trials have shown that OTDOA [Observed Time Difference of Arrival] "is able to provide accuracy within a few tens of meters both indoors and outdoors when carriers deploy and configure their networks appropriately," it adds that OTDOA has not been sufficiently tested yet and that its deployment "will require extensive infrastructure improvements and capital expenditure by each carrier." It is reasonable to conclude that the accuracy of cellular-based location determination is at best tens of meters, but it can be as large as couple of hundred meters.

The other technique uses the Global Positioning System (GPS) receiver available in smartphones. The phone simply reports its location based on a GPS fix. This technique works if there are line-of-sight (LOS) propagation paths from the smartphone to at least four GPS satellites. Hence, the smartphone can get a location estimate from GPS outdoors (unless the phone is in an urban canyon), but in most cases, there will not be a GPS fix inside buildings or other structures. According to a [US Department of Defense and GPS](#)

² <https://www.911cellular.com/>

³ S. Jiang, G. A. Fiore, Y. Yang, J. Ferreria, Jr., E. Frazzoli, and M. C. Gonzalez, "A review of urban computing for mobile phone traces: Current methods, challenges and opportunities," in Proc. 2nd ACM SIGKDD Intl. Workshop on Urban Computing (UrbComp), ACM, New York, NY, 2013.

⁴ J. Yang, A. Varshavsky, H. Liu, Y. Chen, and M. Gruteser, "Accuracy characterization of cell tower localization," in Proc. 12th ACM Intl. Conf. on Ubiquitous Computing (UbiComp), ACM, New York, NY, 2010.

⁵ https://apps.fcc.gov/edocs_public/attachmatch/FCC-15-9A1.pdf

[NAVSTAR report](#)⁶ (Page v), the GPS Standard Positioning Service (SPS) has an accuracy of 4 meters rms and 7.8 meters 95%. Furthermore, some well-designed GPS receivers have been achieving horizontal accuracy of 3 meters or better and vertical accuracy of 5 meters or better 95% of the time. A [Google Map document](#)⁷ states that the accuracy of GPS receivers found in smartphones is a few meters. Therefore, GPS is more accurate than cellular-based location determination techniques, but it does not work indoor.

Since the enactment of the 1999 Wireless Communications and Public Safety Act, the Federal Communications Commission (FCC) has been working with the public safety community and the wireless industry to improve location accuracy for E911 calls. This is becoming increasingly important because more than 70% of 911 calls are placed from mobile phones today. The main challenge for E911 calls is accuracy indoors. The latest FCC rules call for achieving 50-meter horizontal accuracy or providing dispatchable location for a minimum percentage of E911 calls ([40% by April 2017, 50% by April 2018, 70% by April 2020, and 80% by April 2021](#)⁸). In addition, the FCC has called for one or more vertical (z-axis) location accuracy metrics to be defined by nationwide providers and certain benchmarks based on those yet to be defined metrics to be met by certain dates.

The First Responders Group (FRG) of the Science and Technology Directorate at the US Department of Homeland Security (DHS) approached NIST to request test & evaluation of the Safety App from 911Cellular.

This document reports the findings of the tests on this App carried out at NIST. It is organized as follows. Section II provides a brief description of how the Safety App from 911Cellular works. Section III describes the testing methodology used by NIST. Section IV presents the test results. Section V considers the issue of how the Safety App would work in environments and buildings other than the one NIST used for testing. Some concluding remarks are presented in Section VI.

II. 911Cellular Safety App

As shown in Figure 1, the Safety App has a very simple operation. Once the person who is in an emergency situation clicks on the “Emergency” button in the Safety App on his/her smartphone, the Basic Service Set Identifier (BSSID) of the Wi-Fi Access Point (AP) the smartphone is connected to is sent over the Internet to the 911Cellular server in the cloud. The server looks up the location of the AP based on the received BSSID, which is unique, and transmits the location to a PSAP along with an appropriate message. The PSAP will make arrangements so that emergency responders are sent to the location of the AP to look for the person needing help. The location can be someone’s home or apartment street address, something like “AP in the corridor next to Room B463” in case of an office building, etc. Basically, one can put whatever description for the AP location, up to so many characters, that makes most sense in the 911Cellular database.

⁶ GPS Standard Positioning Service (SPS) Performance Standard, 4th Edition, Sept. 2008. Link: <http://www.gps.gov/technical/ps/2008-SPS-performance-standard.pdf>

⁷ <https://support.google.com/maps/answer/2839911?co=GENIE.Platform%3DAndroid&hl=en>

⁸ <https://www.fcc.gov/public-safety-and-homeland-security/policy-and-licensing-division/911-services/general/location-accuracy-indoor-benchmarks>

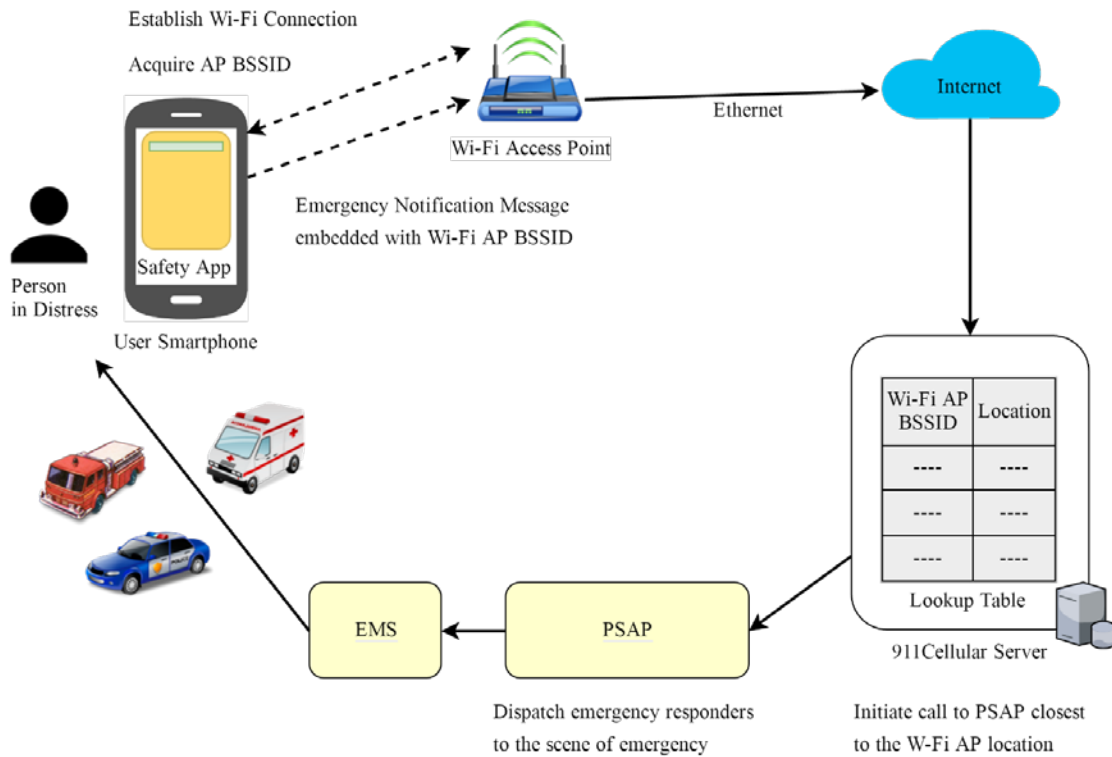


Figure 1- Block diagram showing the operation of 911Cellular Safety App

Two conditions need to be met for the Safety App to do its job. First, the building needs to have Wi-Fi coverage, and the Wi-Fi network needs to be connected to the Internet. Second, the smartphone the App is installed on needs to be connected to the Wi-Fi network. The Wi-Fi network may consist of a single AP or many APs. The former would be the case at a home, apartment, coffee shop, or other small businesses. The latter would be the case in an enterprise environment, such as the Wi-Fi network for a company. The Wi-Fi network may be open or it may be closed requiring login with a password. If the person having an emergency is in a coffee shop with an open Wi-Fi network, and the restaurant next door also happens to have an open Wi-Fi network, chances are the Wi-Fi signal from the AP in the coffee shop is stronger than the one from the AP in the restaurant, and hence the person’s smartphone would be connected to the Wi-Fi AP in the coffee shop. Even though unlikely, there is still a possibility that the smartphone may get connected to the Wi-Fi AP in the restaurant, which results in emergency responders being sent to the neighboring establishment. If the Wi-Fi network the smartphone is connected to is closed, it is less likely that the smartphone is not in the vicinity of the AP it is connected to. For example, many units in an apartment complex may have Wi-Fi networks, and increasingly these networks are closed. Therefore, if the person is at his/her apartment, the smartphone gets automatically connected to the Wi-Fi AP/network in that apartment, because the password for that network is in the smartphone’s memory. When the person clicks on the “Emergency” button in the Safety App, as long as the smartphone is connected to a Wi-Fi AP at the address/location where the person is, the emergency responders would be sent to the right address/location.

The Safety App allows the person who is in an emergency situation to attach a text message, a voice message, photos, or a video clip to the outgoing request for help when he/she clicks on the “Emergency” button. The evaluation of those features is beyond the scope of this report. Interested readers are referred to 911Cellular, LLC for more information on the set of features the Safety App supports. The focus of this report is on evaluating the Safety App’s localization accuracy.

III. Testing Methodology

NIST led the development of the international standard ISO/IEC 18305, Information technology -- Real time locating systems -- Test and evaluation of localization and tracking systems, which was published in November 2016. NIST uses ISO/IEC 18305 in all indoor localization Test & Evaluation (T&E) work that it does. ISO/IEC 18305 treats the system under test as a black box. Specifically, its prescribed T&E procedures have been developed in such a way that they can be used to test *any* localization and tracking system (LTS) regardless of which set of localization sensors or RF techniques the LTS is using. However, since we know how the 911Cellular Safety App works, we used an appropriate subset of the T&E scenarios recommended in ISO/IEC 18305.

III.A Testing Location

We tested the Safety App in a four-story office and laboratory building on the NIST campus in Gaithersburg, Maryland during the period December 14-16, 2016. This building has a rectangular footprint of dimensions 32x112 meters. The labs and offices are in the first three floors of the building. The fourth floor is an attic that is used as temporary storage for furniture and other equipment not actively used. There is also a small penthouse on the fifth floor, but we were not able to do any testing there, because it does not have Wi-Fi coverage. The building has four stairwells, two of which end at the third floor, one that goes up to the fourth floor, and only one that goes all the way up to the fifth floor. We tested the Safety App on the first three floors and all stairwells of the building. The building has a total of 44 Wi-Fi APs installed on the first three floors. This translates into roughly 15 APs per floor and one AP for every 245 square meters of area. In addition, a total of 300 circular floor markers of 3cm-diameter have been deployed in the building that we use as test points for testing indoor LTSs. The precise 3D locations of these test points, which we informally call dots, have been professionally surveyed.

III.B Effects of Mobility on App Performance

Since “for the most part” the manner in which the smartphone is moved around a building does not affect the localization accuracy of the Safety App, there was no need to introduce different modes of mobility into the T&E scenarios that we used. Specifically, there was no need to include T&E scenarios from ISO/IEC 18305 that included walking backwards /sideways, crawling on the floor, or putting the smartphone on a cart and moving it in that manner. We did not test in elevators either, because we do not have any dots in the elevators due to their mobility. Including T&E scenarios involving mobility is only necessary if the localization system uses sensors that are affected by mobility, such as accelerometers and gyroscopes.

III.C AP Handoff Hysteresis Effect

We used the phrase “for the most part” in the previous subsection, because there is a Wi-Fi AP handoff hysteresis effect in how the Safety App works that is an exception to the rule that mobility has no effect on the performance of the App. Suppose the smartphone is connected to a given Wi-Fi AP at some dot and then we move to the next dot. The smartphone may remain attached to the same AP even though there may be another AP whose signal is stronger at the new dot. This phenomenon can happen if the signal from the old AP is not far weaker than the signal from the new AP. As an example of how this phenomenon can affect the performance of the Safety App, consider the long east-west corridors in the building we used for testing. The vast majority of the Wi-Fi APs installed in the building are attached to the ceilings in these corridors. If one visits the dots in one of these corridors starting from the east side and moves towards the west side, as depicted in Figure 2a, the easting component of the error vector will be typically positive, because the smartphone is attached to an AP to the east of each dot in the corridor. (Note that the error is defined as the easting coordinate of the dot subtracted from the easting coordinate of the Wi-Fi AP the smartphone is connected to at a given dot.) On the other hand, if one moves from west to east in the same corridor, as depicted in Figure 2b, the easting component of the error vector will be typically negative. Hence, if in one such corridor one moves from east to west and in another in the reverse direction, the easting components of the error samples would almost cancel out when one computes the overall bias of the Safety App. The errors would not cancel out when one computes the average horizontal error, because that error is computed based on the magnitude of the first two components of the error vector, excluding the vertical component. The AP handoff hysteresis effect would make the horizontal error at a given dot larger. More information about this effect is provided in Section IV.

One way to prevent the AP handoff hysteresis effect to degrade the localization accuracy of the Safety App is to have the person carrying a smartphone turn its Wi-Fi interface off and then on again upon arrival at a new location in the building. This would cause the smartphone to get connected to the Wi-Fi AP with the strongest signal in an enterprise environment where the Wi-Fi network would have many APs. Typically, the strongest signal comes from the closest AP to the smartphone. Hence, turning the Wi-Fi interface off and then on again would typically result in the Safety App producing a more accurate estimate of the location of the person carrying the smartphone. However, expecting the person to turn the smartphone Wi-Fi interface off and on each time the person moves from one point in the building to another is unrealistic. Expecting the person to do so when he/she has an emergency and before clicking on the “Emergency” button of the Safety App is unrealistic. If the person is having a heart attack, there is a good chance the person is unlikely to mess with the Wi-Fi interface before clicking the “Emergency” button.

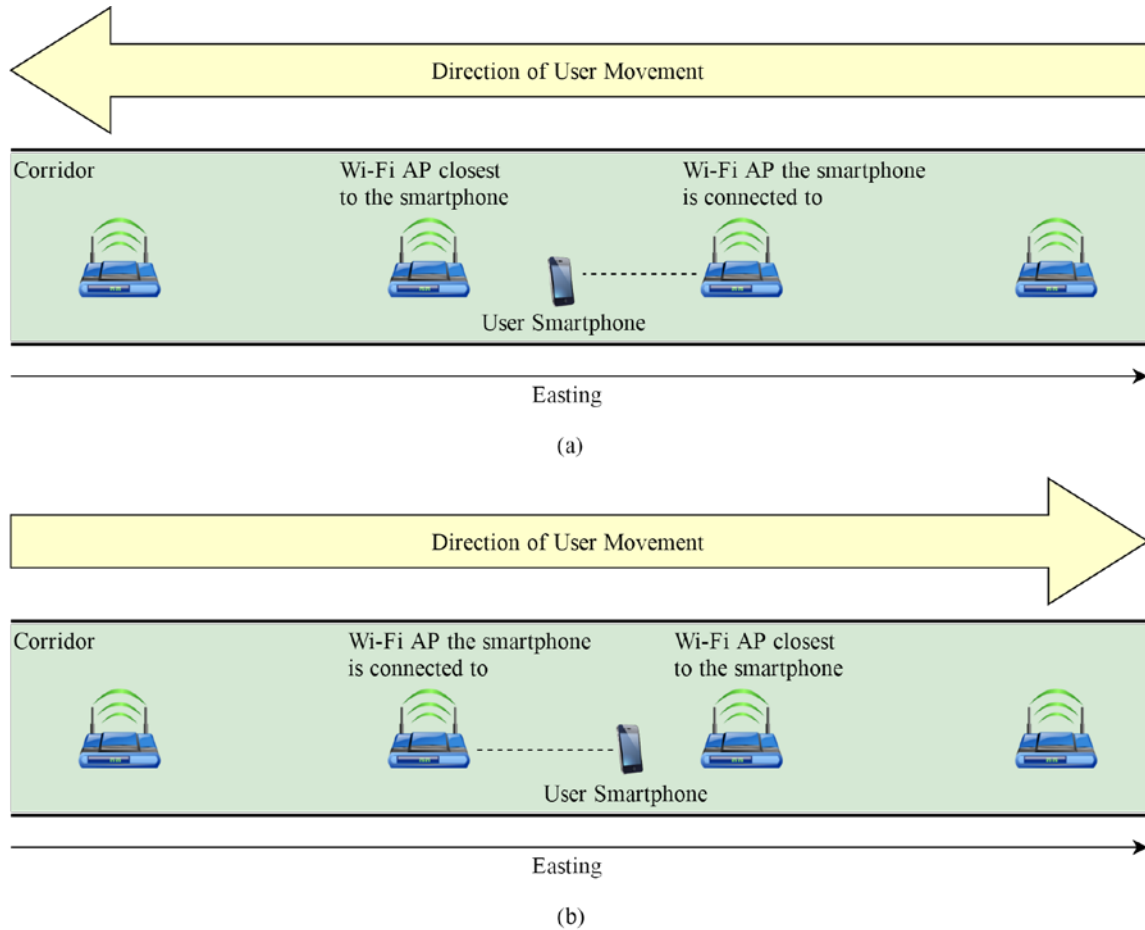


Figure 2- The AP handoff hysteresis effect makes the magnitude of the easting error larger than if the smartphone were to get connected to the closest AP. The easting error is positive in (a) and negative in (b).

III.D Testing Protocol

For the reasons mentioned in the previous subsection, we used a simple testing protocol that ignored the AP handoff hysteresis effect. At each of the 296 dots that we used for testing, the test subject with the smartphone in his right hand stood facing north, west, south, and east and tested the Safety App once for each direction by clicking the “Emergency” button. The reason for testing in various directions was to determine whether it made any difference whether the body of the test subject was between the smartphone and the Wi-Fi AP closest to the smartphone. We wanted to know whether the attenuation of the Wi-Fi signal by the human body would cause the smartphone to get attached to a different AP. At the dots that are installed in offices, we did our testing while the door from the office to the corridor was open. In a second set of tests that were carried out in offices only, the test subject stood facing in the direction that faced the door from the office to the corridor and testing was done while the office door was closed. Once again, we wanted to know if a potential obstacle on the path of the RF signals from the Wi-Fi APs, in this case the closed door, would affect the performance of the App.

IV. T&E Results

In this section, we present the results of our tests in the form of several tables and figures. Many performance metrics have been computed. The definitions of these performance metrics, which are a subset of those given in ISO/IEC 18305, are included in Appendix A.

Table 1 is a summary of the results for the first test, where the test subject stood facing in four directions and tested the App. The total number of tests were 1184, corresponding to four tests at each of 296 dots. There are two ways of dividing these dots into different categories. One is based on which floor (Floors 1-3) a dot is on and the other is based on whether the dot is in an office (also includes laboratories), corridor, or stairwell. While the total number of tests based on the second classification is 1184 (412+660+112), the corresponding number for the first classification is 1132 (324+400+408), because there are a total of 13 dots on Floor 4 and various half-floors (1.5, 2.5, 3.5, and 4.5) in the stairwells.

The following conclusions are drawn from the results presented in Table 1:

- The most important observation is that the overall average horizontal error and CE95 (circular error 95%) are 7.45 m and 15.11 m, as shown on the 2nd and 11th rows of the table, respectively. The latter is particularly important in light of FCC's 50-meter horizontal accuracy for 80% of the E911 calls by 2021. The Safety App from 911Cellular achieves 15.11 m accuracy in 95% of the area of a Wi-Fi-instrumented building today⁹.
- An equally important observation is that the overall floor detection probability is 87.6%. This is important because z or vertical accuracy is a major concern in E911 calls. The Safety App correctly decided from which floor the E911 called was placed in 87.6% of the area of the building. Even though this level of vertical accuracy corresponds to testing in a four-story building (as it was mentioned earlier, we were not able to do any testing on the fifth floor), this performance is scalable to high rise buildings. The smartphone is typically connected to the closest Wi-Fi AP. As long as there are a sufficient number of Wi-Fi APs on each floor of a building, the vertical accuracy is the same regardless of whether the smartphone is on the 2nd floor or on the 100th floor.
- The mean of the magnitude of vertical error is 1.69 m in the stairwells. This is higher than the corresponding figure of 1.09 m for the offices and corridors. This is due to the fact that the Wi-Fi APs are installed in Floors 1-3 in the building, but we have a number

⁹ There is a difference between x% of the calls and x% of the area. NIST could only consider the latter. In order to say anything about x% of the calls, one has to have an idea of which areas in a building the person making an E911 call is more likely to be. One would then use different weights for test results at different dots in the building instead of giving equal weights to all dots, which the 7.45 and 15.11 meter results are based on. It should also be noted that calls from certain locations in a building might be more critical than those from other locations. For example, if someone is having an emergency in the boiler room of a building, that emergency might be more severe than emergencies at other locations in the building. To the best of our knowledge, no one has a good handle on this issue or even how to verify FCC's x% of the calls requirement when one is doing testing at a finite number of locations.

Table 1- Comprehensive results for the first test, where the person stands facing four directions at each dot and a test is done for each direction

Performance Metric	Overall	Office	Corridor	Stairwell	Floor 1	Floor 2	Floor 3
Sample size	1184	412	660	112	324	400	408
Mean of the magnitude of horizontal error	7.45	7.54	7.53	6.59	7.92	6.97	7.80
Mean of the magnitude of vertical error	1.15	1.09	1.09	1.69	1.31	1.13	0.94
Mean of the magnitude of 3D error	7.65	7.69	7.74	6.97	8.22	7.16	7.90
Variance of the magnitude of horizontal error	16.45	7.11	23.45	8.89	21.16	12.85	16.85
Variance of the magnitude of vertical error	0.79	0.65	0.69	1.61	1.41	0.76	0.14
Variance of the magnitude of 3D error	15.49	6.68	22.17	8.24	19.48	12.07	16.30
RMS value of the magnitude of horizontal error	8.48	7.99	8.96	7.23	9.16	7.83	8.81
RMS value of the vertical error	1.45	1.35	1.37	2.11	1.77	1.42	1.01
RMS value of the magnitude of 3D error	8.60	8.11	9.06	7.53	9.33	7.96	8.87
Circular error 95% (CE95)	15.11	12.74	16.18	13.16	17.68	13.61	15.28
Vertical error 95% (VE95)	4.40	2.70	4.40	4.44	4.44	4.41	0.89
Spherical error 95% (SE95)	15.13	12.77	16.21	13.19	17.71	13.63	15.31
Circular error probable	6.96	7.37	6.69	5.41	6.76	6.98	7.48
Vertical error probable	0.87	0.87	0.86	0.92	0.86	0.87	0.87
Spherical error probable	7.08	7.53	6.81	5.95	6.82	7.13	7.53
Floor detection probability:							
Overall floor detection probability	0.876	0.917	0.926	0.429	0.873	0.913	0.953
Number of correct detections on Floor 1	283	84	183	16	283		
Number of samples on Floor 1	324	96	204	24	324		
Floor detection probability on Floor 1	0.873	0.875	0.897	0.667	0.873		
Number of correct detections on Floor 2	365	139	213	13		365	
Number of samples on Floor 2	400	152	232	16		400	
Floor detection probability on Floor 2	0.913	0.914	0.918	0.813		0.913	

Number of correct detections on Floor 3	389	155	215	19			389
Number of samples on Floor 3	408	164	224	20			408
Floor detection probability on Floor 3	0.953	0.945	0.960	0.950			0.953
Number of correct detections on Floor 4	0			0			
Number of samples on Floor 4	8			8			
Detection probability on Floor 4	0			0			
Absolute mean of floor error	0.109	0.083	0.074	0.411	0.127	0.088	0.047
Probability that the location estimate is not the same in all four directions	0.088	0.117	0.073	0.071	0.062	0.110	0.098

of dots in the stairwells at half-floors and a few dots on Floor 4. The location estimate the Safety App produces for dots at half-floors would at best be either at the floor just below or just above the half-floor. The same phenomenon causes the variance of the magnitude of vertical error, the RMS value of the vertical error, and the floor detection probability in the stairwells to be worse than corresponding figures for the offices and corridors.

- Since the vast majority of the Wi-Fi APs are installed in the corridors of the building we used for testing, the horizontal error can be very small or quite large in the corridors. The former is due to the fact that a dot can be just underneath a Wi-Fi AP. The latter is due to the AP handoff hysteresis effect described in Subsection III.C. This explains why the variance of the magnitude of horizontal error, the variance of the magnitude of 3D error, CE95, and spherical error 95% (SE95) are larger in the corridors than the corresponding figures for offices and stairwells.
- For reasons that we cannot explain, the vertical error performance of the Safety App is better on Floor 3 than on Floor 1. (Floor 2 performance figures are in between these two extremes.) This can be seen by examining the values for the mean of the magnitude of vertical error, the variance of the magnitude of vertical error, the RMS value of the vertical error, vertical error 95% (VE95), and floor detection probability for Floors 1-3.
- Floor detection probability does not distinguish between different types of floor errors. The absolute mean of floor error does. For example, if the smartphone is on Floor 3 and it gets attached to a Wi-Fi AP on Floor 2, that would result in a floor error of value 1. If it gets attached to a Wi-Fi AP on Floor 1, that would result in a floor error of value 2.
- The probability that the smartphone gets connected to different Wi-Fi APs depending on which direction the person holding the smartphone is facing is only 8.8%. Therefore, it does not make much of a difference whether the Wi-Fi signal has to go through the person's body or not.

Figure 3 depicts the overall spatial distribution of the horizontal error vectors for all the 1184 tests in the first test as well as a blue circle with radius CE95. Note that there are fewer than 1184 error vectors (shown by red points) in the figure, because the smartphone was connected to the same Wi-Fi AP at a vast majority of the dots regardless of which direction the test subject was facing.

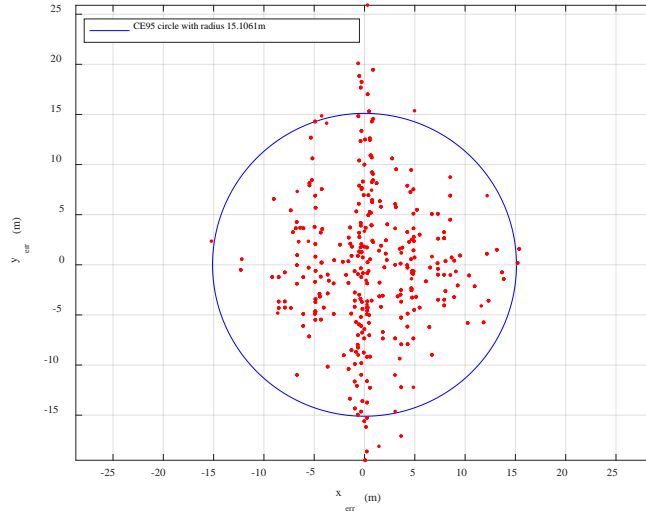


Figure 3- The overall spatial distribution of horizontal error vectors for all the tests in the first test and the associated CE95

Figure 4 shows the spatial distribution of the horizontal error vectors in the first test in the offices, corridors, and stairwells. Also shown are the circles representing CE95s, whose values can be found in Table 1. One interesting observation is the concentration of the error vectors in the middle figure along a vertical line. This is due to the presence of two, long, east-west corridors on each floor of the building we used for testing where most of the Wi-Fi APs are installed.

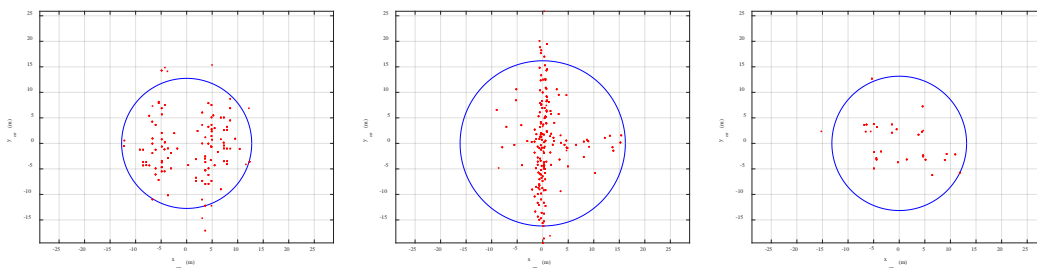


Figure 4- From left to right, the spatial distribution of horizontal error vectors in the first test in the offices, corridors, and stairwells and the associated CE95s

Figure 5 shows the overall histogram of floor errors for all the 1184 tests in the first test. Floor errors with value -1.5 correspond to the single dot on Floor 4.5 (in the stairwell and between Floors 4 and 5), because the smartphone gets connected to a Wi-Fi AP on Floor 3

at this dot. Another interesting observation is that there are no floor errors with values of 2 or -2.

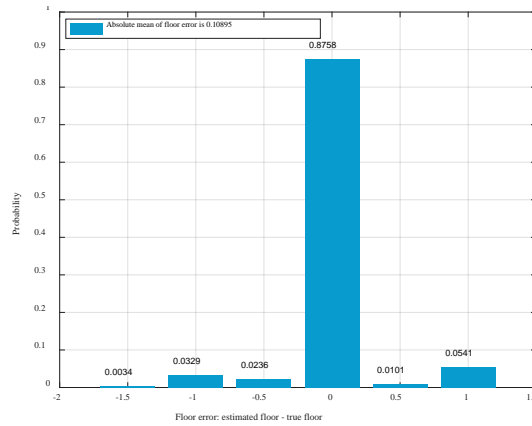


Figure 5- The overall histogram of floor errors for all the tests in the first test

Figure 6 shows the histograms of floor errors in the first test in the offices, corridors, and stairwells. Recall that the Wi-Fi APs are installed on Floors 1-3 only. That is why the histogram looks different for the stairwells. The Safety App has no chance of getting the floor right on the half-floors and anywhere above Floor 3.

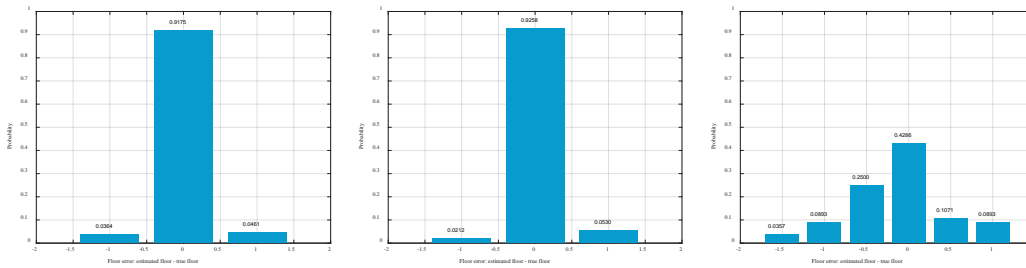


Figure 6- From left to right, the histograms of floor errors in the first test in the offices, corridors, and stairwells

Figures like Figures 4 and 6 for Floors 1-3 of the building as well as some additional test results are provided in Appendix B.

Table 2 presents additional statistics for the 3D error vector in the first test. The first row of the table shows that the Safety App does not have a significant overall bias, which is not a surprise given how it works.

Similar statistics subdivided according to the environment are presented in Appendix B.

The AP handoff hysteresis effect was introduced in Subsection III.C. As a concrete example of how it affects the performance of the Safety App, we examine the localization accuracy of the App along two, long, east-west corridors on each floor of the building used

for testing. On each floor, there is an A corridor and a B corridor. In the A corridors we started on the east side and tested at the dots in those corridors moving towards west. In the B corridors we started on the west side and moved towards east. The mean of the 3D error vector in the A and B corridors are (0.45, 3.27, 0.80) and (-0.01, -4.18, 0.99), respectively. The noticeable difference is in the second components of the errors vectors, which is the easting component. This validates what was said about this specific situation in Subsection III.C.

Table 2- Other statistics of the 3D error vector in the first test

Mean of the error vector	[0.73, -0.05, 0.90]
RMS values for error vector components	[4.84, 6.96, 1.45]
Absolute mean of the error vector	[3.52, 5.32, 1.15]
Covariance matrix of the error vector	$\begin{bmatrix} 22.88 & -0.43 & -0.09 \\ -0.43 & 48.48 & -0.16 \\ -0.09 & -0.16 & 1.31 \end{bmatrix}$

We also carried out a second set of tests in the offices only. In each office that had a dot, the test subject stood in the direction of the office door to the corridor and tested the Safety App with the door closed. This is in contrast with the first test where the test subject tested the app while facing four directions and with the office door open. The purpose of the second test was to determine whether the status of the office doors (open or closed) had any effects on the performance of the App. Table 3 compares the performance of the App when the office doors are open vs. when the office doors are closed. Note that, in the open door case, the results come from only one of the four directions, namely the direction facing the door, so that we would have an apples to apples comparison. These results show that it makes practically no difference whether the office doors are open or closed. As a matter of fact, the closed door results are slightly better than the open door results! This might be due to the AP handoff hysteresis effect again in the sense that in the closed door case the smartphone scans for the strongest Wi-Fi signal as opposed to staying connected to the same Wi-Fi AP. Note that the door attenuates the RF signal from the Wi-Fi APs.

Table 3- Comparison of office doors being open with office doors being closed

Performance Metric	Office Door Open	Office Door Closed
Mean of the error vector	(0.57, -1.04, 0.90)	(0.66, -0.71, 0.87)
Mean of the magnitude of horizontal error	7.88	7.82
Mean of the magnitude of vertical error	1.10	1.08
Mean of the magnitude of 3D error	8.03	7.97
Variance of the magnitude of horizontal error	8.63	10.96
Variance of the magnitude of vertical error	0.69	0.58
Variance of the magnitude of 3D error	8.11	10.24

V. Performance of the Safety App in Other Environments

It is valid to ask how well the Safety App might work in other environments. NIST evaluated the App in only one building. Do NIST's objective performance evaluation results extrapolate to other buildings, and would the App work as well in other places?

To answer these questions, we need to revisit some of the issues discussed in Section II. First, we consider the case where the Safety App is used at someone's home (apartment, townhouse, single-family house, etc.). If the Wi-Fi network at the home is closed, which is the prevalent trend nowadays, the password for the network is stored on the smartphones of the residents of that home and their smartphones would automatically get connected to the Wi-Fi AP installed at that home. In that case, when the Safety App is used during an emergency, there will be a dispatchable address available to the PSAP. If the Wi-Fi network is open, then there is no guarantee that the smartphone of a resident of that home is connected to the Wi-Fi AP at that home, unless all the other Wi-Fi networks the smartphone sees are closed. If the Wi-Fi network at the home is closed and someone visiting that home has an emergency and uses the Safety App, then either that person's smartphone is connected to a neighbor's Wi-Fi AP or the smartphone is not connected to any Wi-Fi network at all. In the former case, the PSAP would get the wrong address, if the neighbor's Wi-Fi network is registered with 911Cellular. In the latter case, the Safety App would still be able to come up with a location based on other RF signals (GPS and cellular) the smartphone is receiving. In this case, the location estimate might not be as good as in cases where the smartphone is connected to a registered Wi-Fi network at that address.

In an enterprise environment, the Wi-Fi network would most likely be closed. In that case, the localization accuracy of the Safety App would depend on the density of the Wi-Fi APs as well as factors affecting RF signal propagation, such as building construction materials, layout, etc. It is fair to ask whether the App's average horizontal accuracy would be as good as 7.45 m in other buildings. (See the mean of the magnitude of horizontal error in Table 1.) One would expect the performance to be not as good if the Wi-Fi AP density is not as high as in the NIST building we used for testing. To have definitive answers to these questions, it is important to test the Safety App in a few other buildings.

VI. Conclusions

NIST tested the Safety App from 911Cellular, LLC in a large building on the NIST campus in Gaithersburg, Maryland. The App is a solution for making E911 calls from smartphones. It would work in buildings that have Wi-Fi access to the Internet and the Wi-Fi APs deployed in the building are registered with 911Cellular. The app was tested in a comprehensive manner according to the procedures of the international standard ISO/IEC 18305. While the FCC rules call for 50-meter horizontal location accuracy or providing dispatchable location for 80% of the E911 calls by April 2021, the Safety App achieved a horizontal accuracy of 15.11 meters or better in 95% of the area of the building and it correctly decided from which floor the E911 call was placed in 87.6% of the area of the building.

Appendix A: Definitions of LTS Performance Metrics

Introduction

The performance analysis of an LTS boils down to comparing the location estimates generated by the LTS under test at a finite number N of test points with the corresponding ground truth coordinates of those points. For $i=1,2,\dots,N$, the following terminology is introduced for “test point” i :

ground truth coordinates:	(x_i, y_i, z_i)
location estimate generated by the LTS:	$(\hat{x}_i, \hat{y}_i, \hat{z}_i)$
3D error vector:	$\underline{\varepsilon}_i = (\varepsilon_{x,i}, \varepsilon_{y,i}, \varepsilon_{z,i}) = (\hat{x}_i - x_i, \hat{y}_i - y_i, \hat{z}_i - z_i)$
l_2 -norm or magnitude of $\underline{\varepsilon}_i$:	$\ \underline{\varepsilon}_i\ = \sqrt{\varepsilon_{x,i}^2 + \varepsilon_{y,i}^2 + \varepsilon_{z,i}^2}$
horizontal error vector:	$\underline{\varepsilon}_{h,i} = (\varepsilon_{x,i}, \varepsilon_{y,i})$
l_2 -norm or magnitude of $\underline{\varepsilon}_{h,i}$:	$\ \underline{\varepsilon}_{h,i}\ = \sqrt{\varepsilon_{x,i}^2 + \varepsilon_{y,i}^2}$

It is assumed that the z -axis corresponds to the vertical direction.

In addition, in some applications of localization and tracking, a coarse granularity is more useful for characterizing the LTS performance than performance metrics based on the terminology introduced above. Specifically, it is of vital importance to correctly decide on which floor of a building the located entity is when firefighters are tasked to extricate someone, e.g. a downed firefighter or a resident, from a burning building. Similarly, it may be adequate in certain applications to just correctly decide in which “zone” of a building floor the located entity is as opposed to estimating the horizontal location with high precision. Therefore, the appropriate performance metrics for these two cases are the probabilities of making correct decisions. To facilitate computing these probabilities, assume the building has F floors, possibly including floor(s) below ground level, and for $j=1,2,\dots,F$, introduce the following notation for floor j :

number of zones:	L_j
floor zones:	$S_{j,1}, S_{j,2}, \dots, S_{j,L_j}$

The performance metrics presented next are “estimates” of certain statistical averages and probabilities. As such, it makes sense to put a $\hat{\cdot}$ above each estimate, e.g. use $\hat{\mu}_{\underline{\varepsilon}}$ as opposed to $\mu_{\underline{\varepsilon}}$. However, in order to avoid clutter, no $\hat{\cdot}$ signs are introduced.

Floor detection probability

Let N_F denote the number of times the floor number is determined correctly when the LTS is tested at the N test points. Then the floor detection probability is estimated by

$$P_F = \frac{N_F}{N}$$

In order to make a decision about the floor number when testing at test point i , one needs a mapping from \hat{z}_i to the floor number. That mapping would be quite simple if the height of all floors in the building is the same and known and the height of the lowest floor with respect to the ground level is known. (It is assumed that $z = 0$ corresponds to the ground level.) The mapping would be more complicated if the floor height varies from one floor to another, the building has entrances at multiple levels, or it has split floors. In such cases, detailed floor plans of the building along with elevation data need to be made available to the LTS.

Note: Some product manufacturers have coined the term 2.5D RTLS to refer to systems that generate an estimate of the horizontal location and the building floor on which the ELT is located. The floor number is regarded as a half dimension in this context, because it may not be as precise as the horizontal location estimate.

Zone detection probability

This metric is defined as a conditional probability, because most likely making the correct decision about the zone would be useless if a wrong decision is made about the floor. Therefore, if $N_{F,Z}$ denotes the number of times that both the floor and zone numbers are determined correctly by the LTS, the zone detection (conditional) probability is estimated by

$$P_{Z|F} = \frac{N_{F,Z}}{N_F}$$

In order to make a decision about the zone number when testing at test point i located on floor j , one needs to have a mapping from (\hat{x}_i, \hat{y}_i) to zone numbers on floor j , i.e. $S_{j,k}$. This can be tricky depending on how complicated the partitioning of floor j by its zones is.

Means of various errors

The mean of the error vector is estimated by

$$\mu_{\underline{\varepsilon}} = \frac{1}{N} \sum_{i=1}^N \underline{\varepsilon}_i$$

It represents the *overall bias* of the LTS, if N is reasonably large. The performance of the LTS can be improved, in the sense of reducing the Root Mean Square (RMS) value of the magnitude of the 3D error vector, by subtracting this bias from the location estimate generated by the LTS. (The RMS values for various errors are introduced shortly.) Note that any carefully designed LTS would have zero overall bias, particularly if the bias is computed over the entirety of results obtained from testing in several buildings. In addition, one may get some insight by computing the bias separately for each building used in testing. For example, consider a situation where the initial location of a person entering a building is estimated with an LTS that is equipped with a GPS/GNSS receiver and the absolute (such as WGS 84) location of the building outer boundary is made available to the LTS. If there is significant error in the initial location estimate of the person or in the absolute location of the building, then this discrepancy may affect all the location estimates computed after the person enters the building. This type of problem can be detected by computing the bias for the given building.

The mean of the horizontal error vector is simply the sub-vector consisting of the first two elements of $\underline{\mu}_{\underline{\varepsilon}}$.

Also, of interest are the means of the magnitudes of horizontal, vertical, and 3D error vectors estimated by:

$$\mu_{\|\underline{\varepsilon}_h\|} = \frac{1}{N} \sum_{i=1}^N \|\underline{\varepsilon}_{h,i}\|,$$

$$\mu_{|\underline{\varepsilon}_z|} = \frac{1}{N} \sum_{i=1}^N |\varepsilon_{z,i}|,$$

$$\mu_{\|\underline{\varepsilon}\|} = \frac{1}{N} \sum_{i=1}^N \|\underline{\varepsilon}_i\|,$$

respectively.

Covariance matrix of the error vector

The covariance matrix of the error vector is estimated by:

$$K_{\underline{\varepsilon}} = \text{cov}(\underline{\varepsilon}) = \frac{1}{N} \sum_{i=1}^N (\underline{\varepsilon}_i - \underline{\mu}_{\underline{\varepsilon}})^T (\underline{\varepsilon}_i - \underline{\mu}_{\underline{\varepsilon}})$$

The diagonal elements of $K_{\underline{\varepsilon}}$ are estimates of the variances of error vector components.

The lower right diagonal element, for example, is the variance of the vertical error.

The trace of $K_{\underline{\varepsilon}}$, denoted by $\text{tr}(K_{\underline{\varepsilon}})$, is the sum of the diagonal elements of $K_{\underline{\varepsilon}}$. $\text{tr}(K_{\underline{\varepsilon}})$ is of particular interest, because it's the square of the RMS value of the magnitude of the error vector once the overall bias has been removed. $\text{tr}(K_{\underline{\varepsilon}})$ is a key metric for an LTS that characterizes performance once the overall bias has been removed.

The off-diagonal elements of $K_{\underline{\varepsilon}}$ are also of interest, because they characterize the correlations between various error vector components. This information may help the LTS designer to improve the system performance by detecting strong correlations and removing them through modifications in system design.

The covariance matrix of the horizontal error is simply the upper left 2x2 sub-matrix of $K_{\underline{\varepsilon}}$.

Variations of magnitudes of various errors

The variances of the magnitudes of horizontal, vertical, and 3D errors are estimated by:

$$\sigma_{\|\varepsilon_h\|}^2 = \frac{1}{N} \sum_{i=1}^N (\|\varepsilon_{h,i}\| - \mu_{\|\varepsilon_h\|})^2 ,$$

$$\sigma_{|\varepsilon_z|}^2 = \frac{1}{N} \sum_{i=1}^N (|\varepsilon_{z,i}| - \mu_{|\varepsilon_z|})^2 ,$$

$$\sigma_{\|\varepsilon\|}^2 = \frac{1}{N} \sum_{i=1}^N (\|\varepsilon_i\| - \mu_{\|\varepsilon\|})^2 ,$$

respectively.

RMS values of various errors

The RMS values for the error vector components are given by:

$$\varepsilon_{x,\text{rms}} = \sqrt{\frac{1}{N} \sum_{i=1}^N \varepsilon_{x,i}^2} \quad \varepsilon_{y,\text{rms}} = \sqrt{\frac{1}{N} \sum_{i=1}^N \varepsilon_{y,i}^2} \quad \varepsilon_{z,\text{rms}} = \sqrt{\frac{1}{N} \sum_{i=1}^N \varepsilon_{z,i}^2}$$

which leads to:

$$\varepsilon_{h,\text{rms}} = \sqrt{\varepsilon_{x,\text{rms}}^2 + \varepsilon_{y,\text{rms}}^2}$$

$$\varepsilon_{\text{rms}} = \sqrt{\varepsilon_{x,\text{rms}}^2 + \varepsilon_{y,\text{rms}}^2 + \varepsilon_{z,\text{rms}}^2}$$

as the RMS values for the magnitudes of horizontal and 3D errors, respectively.

Note that:

$$\varepsilon_{\text{rms}}^2 \geq \text{tr}(K_{\underline{\varepsilon}})$$

with equality iff the overall bias of the LTS is zero (or has been removed).

Absolute mean of the error vector

When the regular mean of an error component is computed, positive and negative errors cancel each other out. This motivates the introduction of the absolute mean of the error vector estimated by

$$\mu_{|\underline{\varepsilon}|} = \frac{1}{N} \sum_{i=1}^N |\underline{\varepsilon}_i| = \frac{1}{N} \sum_{i=1}^N (|\varepsilon_{x,i}|, |\varepsilon_{y,i}|, |\varepsilon_{z,i}|)$$

Circular Error 95% (CE95) and Circular Error Probable (CEP)

CE95 is defined as the radius of the smallest circle centred at the origin in the xy -plane that encloses 95% of $\underline{\varepsilon}_{h,i}$'s. Specifically,

$$\text{CE95} = \min\{R : R \geq 0, |\{\underline{\varepsilon}_{h,i} : i = 1, 2, \dots, N, \|\underline{\varepsilon}_{h,i}\| \leq R\}| \geq 0, 95N\} ,$$

where $|\cdot|$ denotes the size of a set in this context. R95 is an equivalent term to CE95 .

CEP is very similar to CE95 . The only difference between the two is that CEP uses a 50% figure in its definition while CE95 uses 95%. Specifically,

$$\text{CEP} = \min\{R : R \geq 0, |\{\underline{\varepsilon}_{h,i} : i = 1, 2, \dots, N, \|\underline{\varepsilon}_{h,i}\| \leq R\}| \geq 0, 5N\}$$

In general, it is a good idea to plot the empirical Cumulative Distribution Function (CDF) of the magnitude of the horizontal error. This is a staircase function of a single variable r that is zero for all $r < 0$, it jumps by $1/N$ at each empirical value for $\|\underline{\varepsilon}_{h,i}\|$, and it reaches 1 at the largest value for $\|\underline{\varepsilon}_{h,i}\|$ and stays at that level afterwards as $r \rightarrow \infty$. (Note that if there are n samples of $\|\underline{\varepsilon}_{h,i}\|$ that take the value r_0 , then the height of the jump at r_0 would

be n/N . Once this empirical CDF has been plotted, then CE95 and CEP are simply the inverse values of this function at 0,95 and 0,5, respectively.

Vertical Error 95% (VE95) and Vertical Error Probable (VEP)

VE95 is defined as the smallest nonnegative number such that 95% of the $\varepsilon_{z,i}$'s lie in the interval $[-VE95, VE95]$. Specifically,

$$VE95 = \min\{V : V \geq 0, \left| \left\{ \varepsilon_{z,i} : i = 1, 2, \dots, N, \left| \varepsilon_{z,i} \right| \leq V \right\} \right| \geq 0,95N\}$$

VEP is very similar to VE95. The only difference between the two is that VEP uses a 50% figure in its definition while VE95 uses 95%. Specifically,

$$VEP = \min\{V : V \geq 0, \left| \left\{ \varepsilon_{z,i} : i = 1, 2, \dots, N, \left| \varepsilon_{z,i} \right| \leq V \right\} \right| \geq 0,5N\}$$

Once again, it is a good idea to plot the empirical CDF of the absolute value of the vertical error. Once this empirical CDF has been plotted, then VE95 and VEP are simply the inverse values of this function at 0,95 and 0,5, respectively.

Spherical Error 95% (SE95) and Spherical Error Probable (SEP)

SE95 is defined as the radius of the smallest sphere centred at the origin of the 3D Cartesian coordinate system that encloses 95% of $\underline{\varepsilon}_i$'s. Specifically,

$$SE95 = \min\left\{R : R \geq 0, \left| \left\{ \underline{\varepsilon}_i : i = 1, 2, \dots, N, \left\| \underline{\varepsilon}_i \right\| \leq R \right\} \right| \geq 0,95N \right\}$$

SEP is very similar to SE95. The only difference between the two is that SEP uses a 50% figure in its definition while SE95 uses 95%. Specifically,

$$SEP = \min\left\{R : R \geq 0, \left| \left\{ \underline{\varepsilon}_i : i = 1, 2, \dots, N, \left\| \underline{\varepsilon}_i \right\| \leq R \right\} \right| \geq 0,5N \right\}$$

Once again, it is a good idea to plot the empirical CDF of the magnitude of 3D error. Once this empirical CDF has been plotted, then SE95 and SEP are simply the inverse values of this function at 0,95 and 0,5, respectively.

Appendix B: Additional T&E Results

For the sake of completeness, we include in this appendix additional test results that we regard as less important than those in the main part of this report.

Figure B.1 shows the spatial distribution of the horizontal error vectors in the first test on Floors 1-3 of the building and the circles representing CE95s, whose values can be found in Table 1.

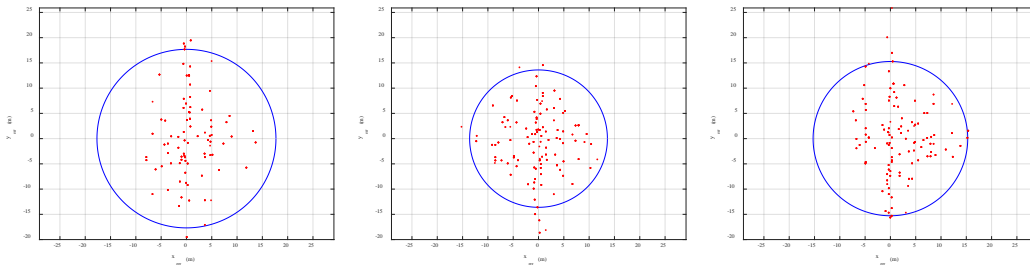


Figure B.1- From left to right, the spatial distribution of horizontal error vectors in the first test on Floors 1-3 of the building and the associated CE95s

Figure B.2 shows the histograms of floor errors in the first test on Floors 1-3 of the building.

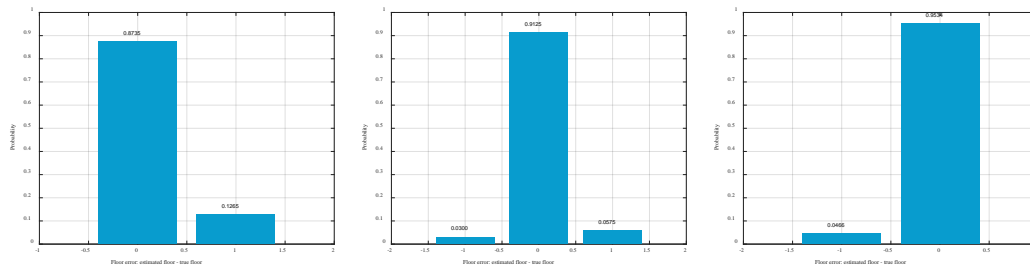


Figure B.2- From left to right, the histograms of floor errors in the first test on Floors 1-3 of the building

A number of additional statistics for the 3D error vector in the first test are presented in Table B.1 subdivided according to the two classifications of spaces in the building.

Table B.1- Other statistics of the 3D error vector in the first test according to the environment

Office	Mean of the error vector	[0.67, -0.79, 0.90]
	RMS values for error vector components	[6.01, 5.28, 1.35]
	Absolute mean of the error vector	[5.56, 4.19, 1.09]
	Covariance matrix of the error vector	$\begin{bmatrix} 35.64 & 0.96 & -0.03 \\ 0.96 & 27.21 & 0.08 \\ -0.03 & 0.08 & 1.03 \end{bmatrix}$
Corridor	Mean of the error vector	[0.77, 0.40, 0.98]
	RMS values for error vector components	[3.69, 8.16, 1.37]
	Absolute mean of the error vector	[1.97, 6.32, 1.09]
	Covariance matrix of the error vector	$\begin{bmatrix} 13.00 & 0.34 & 0.06 \\ 0.34 & 66.44 & -0.09 \\ 0.06 & -0.09 & 0.93 \end{bmatrix}$
Stairwell	Mean of the error vector	[0.66, -0.03, 0.40]
	RMS values for error vector components	[5.88, 4.21, 2.11]
	Absolute mean of the error vector	[5.11, 3.58, 1.69]
	Covariance matrix of the error vector	$\begin{bmatrix} 34.10 & -10.39 & -1.25 \\ -10.39 & 17.68 & -1.69 \\ -1.25 & -1.69 & 4.31 \end{bmatrix}$
Floor 1	Mean of the error vector	[0.76, 0.47, 1.31]
	RMS values for error vector components	[4.36, 8.05, 1.77]
	Absolute mean of the error vector	[3.03, 6.20, 1.31]
	Covariance matrix of the error vector	$\begin{bmatrix} 18.42 & 1.01 & 0.11 \\ 1.01 & 64.62 & -0.93 \\ 0.11 & -0.93 & 1.41 \end{bmatrix}$
Floor 2	Mean of the error vector	[-0.13, -0.65, 0.96]
	RMS values for error vector components	[4.78, 6.21, 1.42]
	Absolute mean of the error vector	[3.54, 4.88, 1.13]
	Covariance matrix of the error vector	$\begin{bmatrix} 22.79 & -0.81 & 0.10 \\ -0.81 & 38.12 & -0.19 \\ 0.10 & -0.19 & 1.10 \end{bmatrix}$
Floor 3	Mean of the error vector	[1.64, 0.06, 0.70]
	RMS values for error vector components	[5.26, 7.08, 1.01]
	Absolute mean of the error vector	[3.79, 5.36, 0.94]
	Covariance matrix of the error vector	$\begin{bmatrix} 24.94 & -1.93 & 0.18 \\ -1.93 & 50.06 & 0.47 \\ 0.18 & 0.47 & 0.54 \end{bmatrix}$