Real Time Range Tracker (RTRT):
Range Accuracy Performance

Sean T. Fursdon and Christine M. Madden
Space and Naval Warfare Systems Center Atlantic
North Charleston, SC USA
{sean.fursdon, christine.m.madden}@navy.mil

Abstract—An Android application (app), called Real Time Range Tracker, was developed as part of a Naval Innovation Science and Engineering program and provides near-real-time “line of sight” range between mobile smart devices. In order to properly design tests and analyze test results, the accuracy of the data generated by the app must be fully understood along with any associated measurement uncertainties. This paper discusses the methods used to assess the app’s performance and results analysis of the range accuracy. The app's stationary range accuracy was found to be 4.2 meters (13.8 feet) and the mobile-to-mobile range accuracy was found to be 95.7 meters (314 feet) for speeds up to 70 mph and ranges up to 20 miles apart. Additionally, sources of accuracy error are discussed and quantified. Based upon this information, a worst-case accuracy prediction equation is provided for cases where test conditions are known. This equation was found to adequately predict an accuracy that was worst-case when compared to actual data sets obtained during testing.

Keywords—location tracking; real-time data; range calculation; Android; software application; mobility; mobile smart device; cellular; test and evaluation; land-based vehicles; Global Positioning System; measurement error; accuracy; uncertainty

I. INTRODUCTION

A simple means did not exist within Space and Naval Warfare Systems Center (SPAWARSYSCEN) Atlantic to determine the real-time range between two moving vehicles in support of test activities. Testing was limited to recording position information for each vehicle and analyzing data after the test event concluded in order to determine the range achieved. This post processing of data was cumbersome, introduced inefficiencies, and increased the risk of retest if the desired range was not maintained. As a result, a Naval Innovation Science and Engineering (NISE) project was created to address this capability gap and to test the following hypothesis: if position information is constantly shared between mobile smart devices, the devices can be used to provide near real-time position and range calculations in support of testing mobile platforms. Although commercially available applications (apps) exist that can track mobile smart devices and display their corresponding locations on a map, none of these products provided the required “line-of-sight” range between two devices in near real-time. Other technologies also canvassed did not meet the refresh rate and range requirements or required purchase of additional equipment. Due to these issues the project focused on development of an Android app, called Real Time Range Tracker (RTRT), that could be deployed on existing government-owned smart devices [1]. In addition to developing the app, the project analyzed the accuracy of the range data presented, which is documented by this paper. As with any test capability, data fidelity must be fully understood and any measurement uncertainties known in order to correctly analyze the test results and to design tests that properly address measurement errors.

II. BACKGROUND

A. RTRT Application Design

The RTRT app was developed using the Android Software Development Kit (SDK) provided by Google. The SDK provides numerous built-in functions to access various sensors and capabilities of a mobile smart device. The RTRT app was designed to operate on mobile devices running Android Application Program Interface (API) versions 10 (Gingerbread) and higher. The app obtains location data from the mobile device’s built-in sensors and transmits this location data over a network (cellular or Wireless Fidelity (WiFi)) to a second mobile device. The user has the option of selecting Global Positioning System (GPS) or fused data for tracking the device’s location. Implemented through the Google Services API, the fused location service provides the app with the best available location data from available location providers, such as WiFi and GPS. Once data from the second device is received, the RTRT app processes the data and displays the latest location and range information on the screen to the user. The location data of both devices and the range data are stored in a Structured Query Language (SQL) Lite database and outputted as Comma Separate Variable (CSV) and Keyhole Markup Language (KML) files at test completion. A high-level conceptual design for the RTRT app is shown in Fig. 1. Details regarding the RTRT app requirements, coding, and internal logic have been documented [1] [2] [3].

B. Mobile Device Specifications

Although the RTRT app can function with any device running Android API versions 10 and higher, Samsung Galaxy S5 phones, model SM-G900V (G900V.05 hardware set), provided by SPAWARSYSCEN Atlantic, were used to evaluate the RTRT app. Samsung Galaxy S5 phones are powerful mobile smart devices that possess many capabilities including a 2.5 Giga Hertz (GHz) quad core processor, 2 Giga Bytes (GB) of Random Access Memory (RAM), Long-Term Evolution (LTE) cellular technology, a Universal Serial Bus (USB) 3.0 interface,
a 5.1-inch high definition display, 16 GB of internal memory, a 2800 milliAmp-hour (mAh) battery, and various built-in environmental sensors [4]. The Qualcomm Snapdragon 801 (MSM8974AC) processor employed in the Galaxy S5 includes Qualcomm IZatTM Gen8B location services that can process data from a variety of sources such as satellites, WiFi networks, cellular networks, mobile device sensors, and cloud-based server augmentation [5] [6]. When satellite coverage is available, the location service utilizes Global Navigation Satellite System (GNSS) receiver chipsets to process GPS and other navigation satellite data with 3 meter accuracy or better under ideal conditions [7].

**C. Network Connectivity**

The cellular data network is ideal for mobile testing purposes due to its wide area coverage, high data throughput, high reliability, and inclusion as part of most cellular plans. Cellular network performance is dependent upon numerous factors and ultimately effects the overall performance of the RTRT app. In particular, the following is specified with respect to Verizon cellular coverage, which was the cellular provider utilized for this effort: “The coverage areas do not guarantee service availability and may include locations with limited or no coverage. Even within a coverage area, there are many factors, including customer’s equipment, terrain, proximity to or inside buildings, foliage, and weather that may impact service. Some of the coverage areas include networks run by other carriers, the coverage depicted is based on their information and public sources, and we cannot ensure its accuracy [8].” Carrier grade Network Address Translations (NAT) employed within many cellular networks prevent mobile devices from directly communicating. Thus, the direct data exchange functionality required by the RTRT app was achieved through a third-party service [9].

**D. Data Exchange**

Implemented within the RTRT app, PubNub, a third party service, facilitates the near real-time data exchange between the mobile devices over the Internet. The PubNub technology is based upon a publish/subscribe model for near real-time data connectivity, providing unicast (one-to-one) communications via dedicated channels. PubNub provides free services for 20 connected devices, 2 kilo Byte (KB) size messages, under 0.25 second latency, Advanced Encryption Standard (AES), and 99.999% availability guarantee across its infrastructure. PubNub also provides a free Android SDK to facilitate easy setup of data communications between apps and the PubNub infrastructure [9] [10]. The RTRT app’s network latency is predicated, in part, on the associated latencies inherent to the PubNub backbone architecture.

**E. Range Calculation**

Once the RTRT app receives a location from the second mobile device, the range is calculated between the two devices based upon the relative timestamps of the location data. The app employs a range calculation routine that utilizes the inverse solution of geodesics for an ellipsoid approximation for the Earth as published by T. Vincenty [11]. Vincenty reports that the range distances obtained from this inverse solution may be in error up to 0.5 millimeters (mm) [11]. Section IV.B provides additional details on how this calculation is achieved within the RTRT app.

**III. RTRT TESTING**

Developmental testing of the RTRT app was performed both stationary and mobile during the period from 20 May to 28
August 2015 [12]. The purpose of the testing was to determine the performance and evaluate the functionality of the RTRT app. This paper focuses on a subset of this data in order to determine the accuracy performance.

A. Test Setup

The RTRT app was installed on two government-owned Samsung Galaxy S5 devices, which were connected to the Verizon cellular network. Although the app is capable of operating over various cellular provider networks, the Verizon cellular provider was used during the test event. The mobile devices had numerous other apps installed and operating (such as background tasks), but during the tests, no other apps were actively running in the foreground and attempts were made to stop any superfluous services running in the background. During mobile testing, a Bluetooth On-Board Diagnostic (OBD) 2 reader manufactured by BAFX Products was installed in each vehicle and was paired to a Torque Pro app to record vehicle conditions [13]. The two Galaxy S5 devices (denoted Mobile Device A and B) were running Android API versions 5.0 and 4.4.4 respectively at the time of the test.

To minimize time inaccuracies, the system times on the mobile devices were synchronized with each other and to the GPS time fix. Automatic time synchronization requires root access to the mobile device, which was not allowed on the devices provided by SPAWARSYSCEN Atlantic. Due to this limitation, time synchronization was achieved via a manual process utilizing additional third-party apps [14] [15]. When manually set, the time was not perfectly synchronized so deviations up to 10 milliseconds (ms) were observed between the devices and within 1 second between the device system time and the GPS time fix. Additionally, the deviation appeared to change constantly and would often drift further apart over time. The results published in this paper do not account for the time differential between the system times of the two mobile devices, but do address discrepancies between the system time and GPS time fix.

B. Test Locations and Routes

The RTRT app was tested at various known stationary locations identified in Fig. 2, which are associated with National Geodetic Survey (NGS) Permanent Identifier (PID) markers [16]. Location data was recorded for approximately 1 hour at each stationary test location. Additionally, the RTRT app was tested from a mobile perspective in and around Charleston, SC along with other locations. Two vehicle condition profiles (Test Profile 1 and 2) were tested along Interstate (I)-26 in South Carolina, which is the primary route utilized for this analysis. This test route, which heads northwest of Summerville, SC, was traveled at speeds up to 70 miles per hour and is a straight stretch of road with adequate GPS and cellular network coverage. Test Profile 1 is broken into segments based upon the relative direction of the vehicles: (Segment 1) vehicles driving towards each other, (Segment 2) vehicles passing and driving away from each other, (Segment 3) vehicle 2 turning around and following vehicle 1 at a constant range, and (Segment 4) vehicle 1 stopped while vehicle 2 driving towards vehicle 1. Test Profile 2 consists of vehicle 2 following vehicle 1 while maintaining a range of 20 miles. These test runs were repeated with the RTRT app in GPS mode and fused location mode. To quantify the worst case network conditions, mobile test data recorded between the states of Washington and South Carolina was also considered.

IV. RTRT PERFORMANCE ANALYSIS

A. Stationary Analysis and Performance

Multiple stationary tests were conducted at known locations to determine the inherent accuracy of the GPS receiver built into the Samsung Galaxy S5. The location data recorded by the RTRT app was compared to the known latitude and longitude of the NGS PID survey markers. The discrepancy between the RTRT recorded position and the NGS PID marker, which represents the GPS accuracy, was calculated using the inverse Vincenty method:

\[
\text{Accuracy}_{GPS} = \left| \text{Vincenty}(\text{position}_{\text{RTRT}}, \text{position}_{\text{PID}}) \right|
\]  

When averaged over all the stationary locations for both mobile devices, the accuracy associated with the Samsung Galaxy S5 GPS was found to be 4.2 meters (13.8 feet) with a standard deviation of 1.4 meters (4.7 feet). This measured GPS accuracy was approximately 1.3 meters (4.3 feet) greater than the value reported in Section II.B. A box plot showing the results for each NGS PID and each device (denoted A and B) are provided in Fig. 2. Data considered possible outliers are not shown on the boxplot.

The results also show that the Mobile Device A’s GPS was generally more accurate than Mobile Device B’s GPS by approximately 1.3 meters (4.3 feet). When the accuracy was plotted versus time for each stationary test, most of the data sets showed large spikes at the very beginning and end of the test. Based upon this observation, it is recommended that the RTRT app is started at least one minute prior to commencement of the test event and stopped one minute after the test event concludes in order to minimize GPS inaccuracies. Additionally, the data points corresponding to the accuracy spikes should not be considered when analyzing the RTRT log files.
B. Mobile-To-Mobile Analysis

To calculate the RTRT accuracy for the mobile-to-mobile test runs, the range displayed on the RTRT Graphical User Interface (GUI) must be compared to the actual range of the two mobile devices at that point in time. Equation (2) is the general accuracy equation used for this analysis and includes both the range error and uncertainty, where the term “A” refers to the range accuracy and “t” refers to the range.

\[ A_r = |r_{ACTUAL} - r_{DISPLAYED}| \pm r_{UNCERTAINTY} \]  

Equation (2)

A detailed depiction of how the accuracy is determined from the RTRT log files is provided in Fig. 3. For the purposes of this analysis, all calculations are made with respect to the data produced on one mobile device (referred to as mobile device 1), which is the device where the GUI was observed. Mobile device 2 refers to the distant end device that transmitted its location data to mobile device 1.

As part of the app design, a timestamp (t1GUI) is recorded each time the RTRT GUI is updated and a range is displayed. The displayed range (rDISPLAYED) will most likely not match the actual range (rACTUAL) at time t1GUI due to time delays associated with transmitting the location data between the two mobile devices, subsequent data processing, and other factors discussed in II. During this delay, the two vehicles have moved from their original recorded locations. To determine the actual range, the exported RTRT log files from the two devices must be post processed. The actual location of each mobile device is determined by finding the closest recorded GPS timestamps (t1,2GPS) to time t1GUI. The location data associated with timestamps t1,2GPS are inserted into the inverse Vincenty method to determine the “actual” range most approximate to time t1GUI.

As part of the logging feature, the RTRT app also records the latitude and longitude for each device used to calculate the range rDISPLAYED. Every time mobile device 2’s location data (at timestamp t2GPS) is received by mobile device 1, the app looks up the location data timestamp (t1GPS) for mobile device 1 that most closely matches t2GPS. The app then uses the inverse Vincenty method to calculate the range between these two locations that is later displayed on mobile device 1’s GUI.

The timestamp approximation errors (t1,2ERR) along with the inherent GPS receiver inaccuracy (A1,2GPS) comprise the uncertainties associated with the range accuracy calculation.
Equation (3) was developed to describe the overall range accuracy and uncertainty.

\[
A_r(t_{GUI}) \approx |r_{ACT}(t_{GUI}) - r_{GPS}(t_{GUI})| \pm |t_{1ERR}(t_{GUI}) \times v_1(t'_{GUI}) + t_{2ERR}(t_{GUI}) \times v_2(t'_{GUI}) + A_{1GPS} + A_{2GPS}|
\] (3)

The effect of the approximation errors on the range accuracy can be estimated by multiplying \(t_{1,2ERR}\) by the recorded speed of the mobile device \((v_{1,2})\) at the timestamp \((t'_{GUI})\) closest to \(t_{GUI}\). The speed for each vehicle was recorded throughout the test event using the Torque app. The uncertainty associated with mobile devices 1 and 2 are determined from (4) and (5).

\[
\begin{align*}
t_{1ERR} &= (t_{2GPS} - t_{2GPS}) + (t_{1GUI} - t_{1GUI}) + (t_{1GPS} - t_{1SYS}) \\
t_{2ERR} &= (t_{1GUI} - t_{1GUI}) + (t_{2GPS} - t_{1SYS})
\end{align*}
\] (4, 5)

The last terms in (4) and (5) account for time synchronization errors between the GPS time \((t_{GPS})\) and the mobile device’s system time \((t_{SYS})\).

C. Mobile-To-Mobile Performance

Fig. 4 shows the range as a function of time for one of the Samsung Galaxy S5s (Mobile Device A) during one test run of Test Profile 1. As highlighted in the graph, the range displayed on the RTRT GUI was found to generally lag the actual range by approximately 1 second. Additionally, the graph shows that the conditions of the test vehicles changed as expected during the different segments of Test Profile 1 (described in III). The calculated range accuracy over time is shown in Fig. 5.

Across all runs for Test Profile 1, the average range accuracy for when the vehicles were driving towards each other (Segment 1) was 59.43 meters (194.99 feet) with a standard deviation of 24.55 meters (80.56 feet). The average uncertainty of Segment 1 was calculated as \(\pm31.52\) meters (103.41 feet) with a standard deviation of 9.52 meters (31.23 feet). The average range accuracy for when the vehicles were driving away from each other (Segment 2) was 62.61 meters (205.42 feet) with a standard deviation of 28.25 meters (92.70 feet). The average uncertainty of Segment 2 was calculated as \(\pm32.95\) meters (108.10 feet) with a standard deviation of 7.93 meters (26.03 feet). The range accuracy tended to 0 meters (0 feet) when the vehicles drove in the same direction at a constant range (Segment 3). For the case where one vehicle was stopped (Segment 4), the range accuracy was approximately half of when both vehicles are traveling towards each other.

These observations confirm that the relationships between the RTRT range accuracy error and vehicle velocity (speed and direction) are approximately linear. The results show that the average range accuracy magnitude of Segment 1 and Segment 2 are approximately equal and represent the worst case condition. Based upon this observation, it is recommended that a range accuracy of 95.7 meters (314 feet) is generally assumed for the RTRT app when traveling at speeds up to 70 mph and ranges up to 20 miles apart.

D. RTRT Performance Trends

In addition to establishing the range accuracy, the various test data sets were also analyzed to determine general RTRT app performance trends. All of the data sets logged the result that only the LTE cellular network was utilized throughout the test periods. As recorded from the mobile device’s built-in sensors, the cellular signal strength was between -126 and -54 decibels per milliwatt (dBm) and the location accuracy was between 3 and 17 meters. Location data was received from the mobile device’s built-in GPS and displayed by the RTRT app at an average rate of approximately once per second. The app received location data multiple times a second and yielded much larger data sets when the fused location mode was selected. In general, the fused location mode resulted in noisier range accuracy versus time plots than the GPS only location data sets.
Additionally, the self-reported accuracy for the fused location data was typically greater (worse) than the GPS only location data. Based on these observations, it is recommended that
the RTRT app is used in GPS mode (not fused mode) for the most accurate range results.

The RTRT design diagram, Fig. 1, depicts various time delays associated with RTRT operations and is defined by (6).

\[
\begin{align*}
\Delta t_{\text{XMT}} &= \Delta t_1 \text{ or } \Delta t_7 \\
\Delta t_{\text{NET}} &= \Delta t_2 + \Delta t_3 + \Delta t_4 \text{ or } \Delta t_8 + \Delta t_9 + \Delta t_{10} \\
\Delta t_{\text{CALC}} &= \Delta t_5 \text{ or } \Delta t_{11} \\
\Delta t_{\text{DIS}} &= \Delta t_6 \text{ or } \Delta t_{12} \\
\Delta t_{\text{GUI}} &= \Delta t_{\text{XMT}} + \Delta t_{\text{NET}} + \Delta t_{\text{CALC}} + \Delta t_{\text{DIS}}
\end{align*}
\]

The average time delays subsequently listed below represent the worst-case values computed across all of the test data sets. The average time to receive the location data and transmit it to the network \((\Delta t_{\text{XMT}})\) was 911 ms. The range calculation by the RTRT app contributed to an average delay \((\Delta t_{\text{CALC}})\) of 278 ms after receipt of position and time information from mobile device 2. The time required to display the range \((\Delta t_{\text{DIS}})\) was 682 ms on average. The average network delay \((\Delta t_{\text{NET}})\), which represents the largest source of delay in the RTRT system, was 989 ms as observed during a fused location data test run. Fused location data introduced significant delays on the network, most likely due to the increased frequency of location data transmission. For the GPS only test runs, the largest network delay of 495 ms on average was experienced during the test route between Washington and South Carolina.

E. Range Accuracy Prediction

Equation (7) was developed to predict the RTRT range accuracy if test conditions are known and the general accuracy value recommended in IV.C is insufficient.

\[
A_P = (\Delta t_{\text{GUI}} \times v_2 + \Delta t_{\text{GUI}} \times v_1) \pm |t_{\text{ERR}} \times v_1 + t_{\text{ERR}} \times v_2 + A_{\text{GPS}} + A_{\text{GPS}}| \] (7)

For the first term of (7), the values are added when the vehicles are traveling in opposite directions and subtracted when traveling the same direction. The range accuracy is vehicle speed dependent; the greater the speed, the greater the potential for a higher resultant range inaccuracy. Based upon the performance trends discussed in IV.D, the worst-case expected time delay \((\Delta t_{\text{GUI}})\) is 2.86 seconds. Additionally, the worst-case average \(t_{\text{ERR}}\) was calculated at 1.03 seconds. Utilizing these values and the GPS accuracy listed in IV.A, the equation was verified against various test data sets and was found to provide a good worst-case estimate for the RTRT accuracy. The prediction equation provided a worst-case accuracy value for all of the test runs analyzed when compared to the actual accuracy observed. If time delays are measured to quantify actual conditions, an even more accurate prediction can be attained.

V. CONCLUSION AND FUTURE WORK

As part of this project, an Android app, called RTRT, was developed to provide near real-time “line of sight” range tracking between mobile devices. Developed to fulfill a test capability gap, the RTRT app was tested and analyzed to determine the accuracy of the range values presented to the user along with the app’s performance against test requirements. The analysis presented above found that the primary sources of range inaccuracies were from time delays associated with exchanging location data and displaying the range. Fortunately, all of the delays were fairly small and so a range accuracy of 95.7 meters (314 feet) was achieved for vehicle speeds up to 70 mph and ranges up to 20 miles apart. Additionally, a worst-case accuracy prediction equation was provided for cases where test conditions are known. Utilizing the worst-case time delay parameters generated from various test cases, the equation was found to adequately predict the worst-case accuracy. Based upon the stationary test results, it is recommended that the RTRT app is started at least one minute prior to commencement of the test event and stopped one minute after the test event concludes in order to minimize GPS inaccuracies. The data points corresponding to these accuracy spikes, located within 1 minute of app start and stop, should not be considered when analyzing the RTRT log files. It is further recommended that the app is used in GPS only mode (not fused location mode) as the results tended to be more accurate.

For future work, the authors propose conducting follow-on testing utilizing design of experiments to further refine the prediction equation and to better understand the app’s performance against numerous factors, such as various speeds, different routes, degraded cellular networks, and degraded location tracking environments. Comparing the RTRT app’s performance on various mobile device platforms, in addition to the Samsung Galaxy S5, is also desirable. Future efforts to exploit other sensor capabilities and determine their associated accuracy would advance the use of prolific mobile smart devices as multipurpose test tools.

REFERENCES


