Improving Positional Accuracy in Smartphones: Exploration of the Use of a Broadband Global Area Network System in Positional Data Collection

by

Reid Lewis Harwood

A Thesis Presented to the
Faculty of the USC Graduate School
University of Southern California
In Partial Fulfillment of the
Requirements for the Degree
Master of Science
(Geographic Information Science and Technology)

December 2018

To my buttercup. I told you we would get through this.

Table of Contents

List of Figures

List of Tables

Acknowledgements

I am grateful to my mentor, Dr. Laura Loyola, for the direction I needed and my other faculty who gave me assistance when I needed it. I would like to thank my employer, McManis Faulkner, who allowed me to complete some of this work using my office computer. I am grateful for the equipment provided to me by Stanford Hospital and the University of Southern California.

List of Abbreviations

AGPS	Assisted-GPS
BGAN	Broadband Global Area Network
CORS	Continuously Operating Reference Stations
FGDC	Federal Geographic Data Committee
GLONASS	Global Orbiting Navigation Satellite System
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
IMO	International Maritime Organization
NAD	North American Datum
NGS	National Geodetic Survey
PDOP	Position Dilution of Precision
RMSE	Root Mean Square Error
UTM	Universal Transverse Mercator
VGI	Volunteer Geographic Information
WGS	World Geodetic System

Abstract

Location-based data is becoming more and more integrated into our society from internal navigation to food delivery services. Even the collection of positional data once only collected by professionals with survey equipment is now achievable by anyone with a smartphone. Several studies have looked at the positional accuracy of different smartphones and found that they are not as accurate as dedicated GPS receivers are. Previous research has also shown that positional accuracy in smartphones changes when exposed to adverse conditions like building shadows, tree cover, and canyons.

The aim of this study was to see if the use of a Broadband Global Area Network (BGAN) terminal could consistently improve the positional accuracy of a smartphone, and if that improvement was consistent when exposed to adverse conditions. An experiment was designed and used to test the pairing of these devices using NGS benchmarks and historical landmarks as control points. Findings show that the use of a BGAN terminal does influence the positional locations of the smartphone but not in a consistent manner. At some sites, the smartphone improved in its positional accuracy when the BGAN signal was introduced but at others, there was a decrease in positional accuracy. These mixed results lead to no definitive conclusions reached beyond recommendations for future testing.

Chapter 1 Introduction

Location-based data collection is an expanding endeavor used by professional organizations and enthusiasts all over the world. From collecting locations of invasive species to mapping the locations of bird sightings, to surveying underground utilities and mapping archaeological sites, locational data collection takes many forms. At the root of all of these practices is positional data. Knowing the exact location of where a bird sighting occurred or where an invasive species is located is critical for creating a map, performing analysis, or ensuring someone is not in danger of disturbing an underground utility line. Accurate positional data collection is even more critical for scientific studies that want to show where certain phenomena occur and for certain asset management and control.

Several different types of receivers are available for use with varying positional capabilities. From basic commercial grade GPS receivers like those made by Garmin or Trimble, to high end models capable of sub-meter accuracy like the Trimble Geo XH 6000 or 7 series receivers, and even smartphones equipped with GPS chips, GPS enabled devices are almost everywhere. This presents the problem of which type of receiver is most suitable for a particular purpose. Studies conducted for scientific research or for industrial uses often need receivers that are capable of the highest positional accuracy available in order to produce the highest quality outputs and analytical results. These devices are expensive, resulting in only a few receivers being available to a survey team.

An alternative that could reduce costs for a study, depending on the needs, would be to use smartphones (or tablets) with augmented positional accuracy to conduct this research. Current smartphone technology allows for positional accuracy between 5 – 7 meters but is unreliable. Pairing smartphones with a Broadband Global Area Network (BGAN) terminal (or other satellite receiving antennae capable of producing a Wi-Fi signal) has the potential to help improve the recorded positional accuracy, which would allow for their use in scientific research. Though these units and added capabilities can increase costs, there is the potential for a large return on the investment with a higher quality product for analysis. This thesis examines the improved positional accuracy that can be attained in a variety of urban and rural setting and explores the costs and benefits of this type of investment. The readings from the smartphone and BGAN pairing are compared to the readings from an established data collector used in scientific studies, the Trimble Geo XH 6000.

1.1. Motivation

The current technology used by many scientific studies concerned with positional locations are high end receiving models like the Trimble Geo XH 6000 and Geo 7 series, which as a standalone receiver is capable of sub-meter accuracy in ideal conditions and when paired with a Zephyr antenna can reach sub-centimeter accuracy. When faced with difficult conditions like tree cover, steep canyons, or even building shadows, standalone receivers are paired with other pieces of technology like a base station or an extended antenna to improve accuracy. However, this can cause other problems as experienced by the Point of Beginning (2009) survey team in the Amazon jungle in Peru.

The Point of Beginning team faced the issue of canopy cover interfering with positional data collection. The team wanted to collect the boundaries of a village using a Trimble Juno receiver but encountered problems when attempting to collect points underneath the thick jungle canopy. This same problem has been experienced by many others in the field of archeology (Hester et al. 2009). To solve this problem, the survey team used a Nikon NPL-352 total station to improve their results. The Nikon NPL-352 total station is a survey grade measurement station that can measure sight lines up to 200 meters. These pieces of collection technology are very expensive and cumbersome to carry around a jungle for point collection.

An alternative could be to include a BGAN system, which consists of a terminal that connects to a system of satellites that then provides Internet, and telephone access in remote locations. The satellites used by BGAN terminals are maintained by Inmarsat and consist of four main satellites that are geosynchronous in orbit and do not require mission planning to access the satellites. The capabilities and background of the Inmarsat satellite network is covered more extensively in section 2.4. Improving smartphone positional accuracy may be possible because every BGAN terminal is equipped with a GPS chip, which must acquire a positional fix prior to connecting to the Inmarsat satellite network which then provides Internet or phone services (Inmarsat 2013). Because of this, BGAN terminals may be capable of acting as an improvised mobile base station by providing a known fixed location closer to the study site that receivers could pair with. However, positional data collection is not the intended use of these systems and to date no research has been done in this area to see if it is possible.

BGAN terminals have other features that would also benefit field research. They are small and lightweight which makes them ideal for carrying around difficult terrain, yet they are sturdy and durable allowing them to be taken into harsh or rugged areas without the fear of breaking them. The terminals are able to be set up once and provide a continuous signal across their respective areas of influence. The terminals can then be paired with any Wi-Fi enabled device to access the Internet via the broadband connection. The goal of the study is to see if using a BGAN terminal can consistently improve the positional accuracy of a paired device with GPS capabilities.

1.2. Current Uses of BGAN Terminals & Possible Applications

First responders are the most common users of BGAN systems in the field currently, especially when they are responding to disasters in areas that do not have established communication infrastructure. An example of this is with the San Diego State University “Viz Lab” which collaborated with Inmarsat to provide terminals to wildfire responders who used real time GIS data to respond to expanding wildfires in the San Diego County area (Fire Rescue 2009). While these responders used their terminals in the field to receive real time data, it shows that the connection produced by the BGAN terminal is strong enough to work in remote areas. Unfortunately, it was not stated where the responders were using their terminals and in what kind of conditions, nor does it state what model of terminal was used.

The state of Louisiana (2007) uses BGAN terminals to enable their emergency management teams to provide assistance following a major event, such as in 2005 following Hurricane Katrina. They use multiple terminals to allow for large response areas to be covered with satellite signal in order to provide needed communication systems following a disaster. Each response hub (a centralized response group of medics, managers, and volunteers) that was set up employed a BGAN terminal to be able to communicate with other hubs as well as local hospitals to coordinate their relief efforts. Using these terminals for positional data collection as well would allow first responders or citizens in affected areas to provide valuable support in locating areas and people in need of assistance following such events. This could be possible by creating a Volunteer Geographic Information (VGI) system for people within the affected region to provide relevant information to first responders. This VGI data could consist of photos with geo-location tags or have a field to input addresses to help orientate the responders. If those points are only accurate to 10 or 20 meters, then the responders will still need to conduct a further search of a relative area. If those points are known to be accurate to 1 or 2 meters, then responders would be able to arrive on the scene and know relative locations of people in need of assistance saving valuable time.

Being that BGAN terminals evolved from satellite phone technology, they are mostly used in areas where cellular signal or Internet connections are not available. Currently, there is little use for these terminals in urban settings, especially since the usage fees are very high. However, if needed, they can be employed. An example of how BGAN terminals could be used in an urban setting would be for collecting points in a closed environment like a subway entrance or inside a building. Hofer and Retscher (2017) found that using a Wi-Fi signal with intelligent checkpoints, which are distinctive waypoints within a building like doorways, staircases or elevators marked by their study, was able to improve the internal navigation capabilities of a smartphone inside an office building. Applying their findings to the idea of a BGAN terminal presents the possibility that the Wi-Fi signal generated by the BGAN terminal would be able to improve the GPS receiver of a smartphone connected to that terminal. If the improvement could be continued into a building or a subway station that would present a new urban usage for BGAN terminals, which is not seen currently.

The possibilities of using a BGAN terminal for scientific field data collection are numerous. BGAN terminals provide coverage over a radius between 30 meters and 100 meters depending on the terminal in use. This signal has the potential to be able to extend to areas that are not accessible by GPS signals using current technology, such as under forest canopies, beneath building shadows, or even underground. These environments and various conditions have not yet been tested, but the experiment done for this thesis provide the beginnings of this type of testing for usage in field data collection.

An example of how these systems could be applied to data collection is for site mapping in archaeology. Many archaeological sites are located in areas with conditions that do not provide the best satellite coverage such as underneath a forest canopy, resulting in mapping sites using traditional methods with a measuring tape and direction bearing (Hester et al. 2009). These traditional methods often take an extended amount of time when compared to GPS collection and are often prone to human error. Using a BGAN terminal has the potential to provide signal coverage underneath said canopy allowing the site to be surveyed using GPS collection resulting in more efficient data collection processes and a larger area being covered by a single survey session.

Another collection example would be to place the BGAN terminal at the top of a canyon with the intent that the signal would extend down into the canyon. Once the signal is acquired by the BGAN and it is transmitted to the receiver in the canyon, collection would begin and presumably be improved. This example assumes that the BGAN terminal would be able to improve the positional readings of smartphones, that the signal extends far enough into the canyon to reach the receiver/smartphone, and that the receiver can generate an initial GPS reading that could then be improved by the BGAN signal. While this testing will look at if a BGAN terminal can improve positional readings in a smartphone, it will not go as far as needed to see if this example is possible.

1.3. Research Questions

To determine if a BGAN terminal in conjunction with a smartphone can produce positional data at accuracy levels that are comparable to a Trimble Geo XH 6000 series unit, an experiment has been devised to test each system in the field. This experiment aims to answer the following questions:

- Can a smartphone paired with a BGAN terminal collect points with accuracy levels comparable to a Trimble Geo XH 6000 series unit?
- How does that accuracy change as the distance from the BGAN unit itself changes?
- How does the accuracy change in adverse conditions such as under a forest canopy, in a steep canyon, or in the shadow of a building?

Chapter 2 Literature Review and Background

To understand what steps needed to be taken to assess the positional accuracy of a smartphone paired with a BGAN terminal, several aspects were reviewed. A basic overview of GNSS systems and NGS benchmarks are provided, which are the basis for this experiment. Each piece of technology to be used is reviewed: the Trimble Geo XH 6000 series receiver, the BGAN terminal, and the smartphone to be used along with the data collection applications. Studies that have focused on accuracy testing are also reviewed to understand work that has been completed to date as well as a brief look at cost-benefits for increasing positional accuracy. Finally, this chapter provides a simple explanation of adverse conditions that affect GPS positional readings which will be looked at in this study.

2.1. Global Navigation Satellite Systems (GNSS) and Global Positioning System (GPS)

What most people understand of Global Positioning Systems (GPS) is that they are a network of satellites that allow for a precise fix of a location on planet Earth. While this rudimentary view is not incorrect it does not give a deep enough explanation of how Global Navigation Satellite Systems really work. For the purposes of this report, we focus on the US NAVSTAR Global Position System, referred to as GPS, as this is the satellite system that was used for this report wherein all measurements were taken in the United States.

Any group of satellites capable of determining positional locations on the planet are referred to as Global Navigation Satellite Systems (GNSS). There are many systems in the world that meet this criterion: NAVSTAR GPS, Global Orbiting Navigation Satellite System (GLONASS) the Russian system, Galileo (the European system), and the Chinese Compass Satellite Navigation System (CNSS) to name a few (Bolstad 2012). All of these satellite systems or groups use the same principles when determining positional data. To make that determination, when a receiver accesses a satellite network it connects to as many satellites as possible. This subset of satellites is referred to as a “constellation.” The more satellites in the constellation the receiver connects to, the more accurate the recorded positional data point will be. Each satellite sends out coded signals which can be picked up and interpreted by GPS receivers. Since the speed the signal travels at is known, the time it takes for the signal to be received is used to then calculate the distance of the receiver from the satellite. This process is repeated with other satellites to determine where the receiver actually is. Using only a single satellite will give a large possibility for the location of the receiver as distance is known but not the actual location on the Earth’s surface. By adding other satellites, the receiver is able to narrow down the possible locations until an exact position is determined. If one considers a circle as the area of influence of a satellite with the receiver being somewhere on the edge of the circle, then by adding more circles different intersecting points are found and with enough circles, a single point is found where all the circles intersect.

While many people unfamiliar with GNSS systems in general believe that the stated point is accurate it actually may not be. The accuracy of any recorded positional data point is determined by how many satellites the receiver is able to connect to at any one time due to location difficulties (overhead cover, view of the horizon, and satellite placement). The US NAVSTAR GPS system has approximately 24 satellites in operation at any one time so the possibility of being able to access at least four of these satellites is very good, but not always possible. The Dilution of Precision either horizontal, vertical or positional denotes the uncertainty in a GPS measurement. For the purposes of this study, we are only concerned with Position Dilution of Precision.

2.1.1. Position Dilution of Precision

Position Dilution of Precision, or PDOP, is a complicated measurement that refers to the size of the unknown space determined by the satellite constellation. Bolstad gives an easy to understand explanation in his 2012 work GIS Fundamentals; "The PDOP… is the ratio of the volume of a tetrahedron created by the four most widespread, observed satellites to the volume defined by the ideal tetrahedron." The ideal position of satellites would be one directly overhead and three others spaced evenly around the horizon, but this is rarely observed. PDOP readings are given as a decimal number with 1.0 being the ideal position of satellites and groupings which are less conducive to recording positional data points are given higher PDOP readings. Most receivers will not collect positional data if the PDOP is above the threshold value of acceptable limits.

An underutilized process for improving the positional accuracy of recorded points is a differential correction. Differential correction is the process used to correct any range of errors that may have occurred at the time of collection. The process involves using a secondary receiver, usually set up as a "base station" which is set at a known location and does not move during the collection process. This base station is then used to determine any errors that may have occurred due to satellite movement or obstructions from the receiver and other errors caused by weather or atmospheric conditions. The BGAN terminal used in this study acted as a separate receiver, much like a base station, given that it was connected to a separate satellite network and giving off a continuous signal which should improve the positional readings on paired devices. Inmarsat does state that BGAN terminals contain GPS chips and must acquire a positional reading prior to connecting to their satellite network (Cobham 2015). However, it is unknown how that will affect positional readings on a paired device.

2.2. National Geodetic Survey (NGS) and Benchmarks

The National Geodetic Survey (NGS) is the organization that is responsible for mapping and maintaining geographic charts for the United States (NOAA 2017). NGS established known survey points across the country for the purposes of land surveys and producing maps to ensure accuracy. These points are known as benchmarks and provide precise information on the location at which they are found. The points of interest for this study are the ones that denote a horizontal position, rather than vertical. Historically these points were determined using traditional survey techniques involving distance, declination or angle, and scale. Techniques were enhanced through the 1800s and into the early 1900s using things like a theodolite (a rotating telescope for measuring vertical and horizontal angles), surveyor's compass also called a circumfrencer paired with a chain for measuring distance, and a Bilby Tower (a large tower used for elevating a surveyor above tree canopy or other obstructions) until the advent of GPS.

Today, benchmark points are surveyed using highly accurate GPS receivers often with the assistance of a base station. These points were used by this study to act as the true ground location being assessed, which was then compared to the readings from both the Trimble device and the smartphone both with the assistance of the BGAN system and without it. The exact methods are discussed in the methods chapter.

2.3. Trimble Devices

To understand what constitutes accurate positional data equipment, the study looked at the established collection means using the Trimble Geo XH 6000 Series unit. This unit, and others like it, are widely used in scientific research for collecting points in archaeology, environmental sciences, and even land surveying (Berman 2002, Walter and Schultz 2013, Gerber at al. 2016, Necsoiu et al. 2016, Usmanov et al. 2018). According to the manual for this piece of equipment, the Geo XH 6000 series is capable of recording points within 10 centimeters after correction methods are applied either in real time or in post processing (Trimble 2013). Correction methods include using a reference station to determine the possible error resulting from a poor satellite connection or even the placement of satellites. For a study like Walter and Schultz (2013) where they were mapping skeletal remains that measured less than a single meter, having the equipment to measure objects at sub-meter accuracy was key.

However, Trimble units experience problems when used in adverse conditions. Breman (2002) used Trimble Juno receivers to map the wetlands around Malibu, California, to find areas that were in danger of pollution from surrounding communities. Because of the canopy cover in several spots, the team had to use an external antenna to extend their receivers in order to gain a signal capable of collecting positional data. This study seeks to determine if a BGAN system, placed outside canopy cover, could allow a signal to be acquired and transmitted to a receiver located underneath the canopy thereby eliminating the need for an antenna to reach above the canopy.

Pairing a receiver with a base station is known to produce better positional accuracy results than a receiver alone. This is how Walter and Schultz (2013) were able to achieve replicable results of sub-meter accuracy. The process followed by Walter and Schultz is similar to the one used to determine the effectiveness of using a BGAN terminal in this study.

2.4. Broadband Global Area Network (BGAN) Terminals

BGAN systems are mainly used for gaining access to the Internet in remote locations by accessing a set of satellites maintained by the company, Inmarsat. Inmarsat (Cobham 2015) is the most widely used BGAN satellite platform, has one of the largest satellite networks available, and has been in existence for over 40 years. Starting in 1979 as part of the International Maritime

Organization (IMO), Inmarsat set up its first satellite network to allow ships to communicate with ports and other ships while they were at sea. This communication network was built around satellite phone service and became the foundation for what would become the Inmarsat satellite fleet. The company broke away from the IMO in 1999 and became a private company but still maintains governmental relations in order to continue to provide needed maritime services.

Beginning in the 1980s, satellites were developed that would provide not just phone service but also Internet access to ships at sea (Inmarsat 2013). The first set of satellites capable of providing Internet service were launched in the early 1990s and are known as the I-4 series. While these satellites were only intended to be in use for approximately 10 years, they have been providing services for nearly 25 years for Inmarsat customers, mainly commercial maritime companies and militaries around the world and continue to function properly. Inmarsat is currently deploying their next generation of satellites, the I-5 series also known as the Global Express satellite series which will provide high speed broadband service anywhere on the planet. There are currently 4 satellites of this series in use with more to come, but the older generation, the I-4, still has approximately 13 satellites in use. These I-4 satellites are in geosynchronous orbits at 35,786 KM above the earth and provide services anywhere on the planet except at the poles. When a BGAN terminal is connected to the Inmarsat satellite network, it only connects to one satellite at a time because it only needs access from one satellite to provide Internet or phone services.

The satellites are maintained by Inmarsat, but the terminals are licensed and built by several different companies: Hughes Network Systems, Thrane & Thrane, and Addvalue. For the purposes of this study focused on the Hughes Network Systems models, as that is the model used. The Hughes Network International Model 9201 is capable of providing a signal in a 30-

meter radius and like all BGAN terminals, must acquire a GPS position fix prior to connecting to the Inmarsat satellite network.

In order to use the Inmarsat satellites, a data plan needs to be purchased and paired with a SIM card within the BGAN terminal. Much like a cell phone uses a SIM card, a BGAN terminal does as well to reference a single account and provide data usage information for billing purposes, nothing is ever free. Ground Control (2018) is a major company in providing data packages that allow for access to the Inmarsat satellites. These packages range in size and cost from a few hundred dollars to a few thousand. For this study, 100 MB of data was allotted for field tests and added to the SIM card located within the used BGAN terminal.

The main reasoning for why this piece of equipment could provide improved positional accuracy is the fact that each BGAN terminal comes equipped with a GPS chip internally. The terminal must acquire a GPS position prior to providing an Internet connection. It is assumed that the GPS chip in the BGAN terminal will provide a consistent position that will then be able to improve the positional readings in the smartphone. While the possibilities of using the Internet to facilitate communication between a field team and a research base is intriguing, the leveraging of the internal GPS chip will be the focus of this study.

2.5. Smartphone and Applications

As a BGAN system is only a means for acquiring a signal, the tested terminal must be paired with a collection device. It was decided to use an Apple iPhone 6 paired with the BGAN and loaded with two collection applications, the Fulcrum Data Collection and Esri's ArcGIS Collector (referred to as ArcCollector) applications. The decision to use a smartphone came out of the idea of using technology that is prevalent in modern society and readily accessible in hazards as previously mentioned or for fieldwork. With the availability of smartphones with GPS enabled capabilities becoming more and more common place, having the ability to use those devices in a scientific study would be invaluable. It would allow research to be conducted in large groups and reduce the need for purchasing expensive pieces of equipment for each member of the team.

The Apple iPhone 6 with a service package from AT&T will be used because it is the current smartphone used by the author. As a side note, the inclusion of an Android phone was considered but reliable access to one could not be acquired and funds to purchase one were not available, so this condition may need to be tested in a future study. Most smartphones, including the iPhone, use Assisted-GPS (AGPS) to determine the location of the device. The process involves using cell phone towers and Wi-Fi signals in conjunction with a standard GPS chip to determine the location (Lifewire 2017). While the GPS chips in both the BGAN terminal and the smartphone are the same, the idea of this study is to see if using the pair of GPS chips, one in the BGAN terminal and one in the smartphone, can be leveraged to improve the positional accuracy recorded in by the smartphone.

The purpose of these tests is to find if the use of a BGAN terminal will improve the positional accuracy of the paired smartphone. Because the BGAN system will provide a signal in remote areas where cell phone signal may be minimal or nonexistent, it is believed that the location data recorded by the smartphone will be improved in positional accuracy using the system than without it. It is also plausible that using the BGAN terminal in an area with cellular data signal will still provide more accurate positional data than using just the smartphone alone. This is because the BGAN system will provide another signal paired with a known location that could improve the positional reading of the GPS chip in the phone. The results will be compared to results obtained using the Trimble Geo XH 6000 series receiver.

The Fulcrum Data Collection application is an application that can be customized through the company's website prior to conducting field-testing (Fulcrum n.d.). The information that can be added to a collection form is rudimentary: date and time, a text field for a name, or a self-generated address, and more precise information such as PDOP readings are not available because most smartphones do not provide that information to the application, including Apple. However, the ability to record positional data from the capabilities of the smartphone is all that is required for this study.

Esri's ArcGIS Collector application is also used to collect points to ensure that the BGAN does improve the smartphones capabilities and not just the application. The ArcGIS Collector application works in conjunction with an ArcGIS Online account and can be customized using the online capabilities provided by Esri (Esri 2018). Similar fields can be added to the Arc Collector application as can be done with the Fulcrum application, however the Arc fields must be set up as hosted feature layers using ArcMap or Pro. For this test, similar fields were set up so that the site number, condition, distance and test number could be recorded. The ArcCollector application records positions using the GPS capabilities of the smartphone just like the Fulcrum application does, so using both applications will provide a reference for how the use of the BGAN terminal affected the positional capabilities of the smartphone.

2.6. Positional Accuracy Studies and Standards

Many studies have looked at the positional accuracy capabilities of different GPS receivers such as Walter and Schultz (2013), Zandbergen (2009), and Wing et al. (2005) to name a few. Each study has benefits which can be used going forward and deficiencies that can be learned from. The United States federal government assigned a sub-committee to standardize the way in which positional accuracy is tested and what equations should be used when testing collected data, which are followed in this study.

2.6.1. Positional Accuracy Studies

Walter and Schultz (2013) collected points in an open environment and with the use of differential correction were able to collect points with sub-meter accuracy using a Trimble Geo 7 series receiver, which is comparable in accuracy to the Trimble Geo XH 6000. However, they never tried using their methods in an area that would not have provided the most optimal signal.

Wing et al. (2005) looked at the effects of canopy on commercial grade GPS receivers in Oregon. They found that in ideal conditions the receivers were able to produce results accurate to within five meters and accurate to within ten meters with the most difficult conditions tested. They qualified their conditions as open environment, a young forest, and closed canopy. The study used a digital total station to establish UTM coordinates for each of their testing sites and collected their points in UTM coordinates. Their use of a separate station to determine their control points does not seem to be the best way of establishing control points for testing positional accuracy, especially in conditions that are known to provide inaccurate results (young forests and closed canopies). For this reason, the study used NGS benchmark points as control points so the amount of possible errors in testing sites was reduced as much as possible.

Zandbergen (2009) tested the different location services available on a 3G model iPhone and found several different results. He found that using Assisted-GPS (A-GPS) points had an accuracy of about 8 meters, Wi-Fi positioning around 74 meters, and cellular data positioning to be around 600 meters. He tested the A-GPS positioning type in a static outdoor environment and the Wi-Fi and cellular data enabled in an indoor environment. Zandbergen used high-resolution aerial photos to determine the testing positions of both outdoor and indoor locations. This approach seems even less appropriate for determining ground truth locations due to possible errors in projections or in the images themselves than the method used by Wing et al. (2005) and is further reasoning to use NGS benchmarks for control points. While this study did use satellite photos to determine two of the testing sites, the photos were crossed referenced with historical landmarks that can be found in the satellite image record making them more appropriate to use for control locations.

Initial testing showed that the iPhone 6 that will be used is able to collect points around 5 meters and not exceeding 7 meters in accuracy in ideal conditions, which seems to be an improvement over Zandbergen's study using an older model iPhone. Apple Company does not release any information on signal readings for their products as they consider this information to be proprietary. But it does appear that the GPS capabilities of iPhones have increased with each new model.

2.6.2. Federal Geographic Data Committee (FGDC) Standards

The US federal government has had a need to standardize the way spatial data has been produced and disseminated since the early 1900s. Beginning in 1990 the Federal Geographic Data Committee (FGDC) was established to set down standards for how the nation's digital spatial data will be dealt with. This committee was the one that established the National Spatial Data Infrastructure which laid out standards for how spatial data should be collected, stored, assessed and shared amongst federal agencies. Today, the committee is broken up into several sub-committees all of which are over seen by the Secretary of the Interior

The FGDC has issued standards for how data collection should be conducted and analyzed (FGDC 1998). They state that any points collected should be compared to a point of higher accuracy, but they do not state that a benchmark should be used merely stating a position of higher accuracy. This standard seems odd but does correspond to what has been seen in other studies looking at positional accuracy. They also provide equations for assessing positional accuracy, which were used in the analysis of this study and are covered in the methods section.

2.7. Adverse Conditions for GPS Readings

There are several places that GPS receivers are known to not acquire sufficient signal to determine an accurate position. As mentioned, conditions like forest canopy, tall buildings and steep canyons are all examples of environmental factors that reduce the positional accuracy of any GPS receiver. How each of these conditions affect positional accuracy has been tested by different studies in the past. For example, Wing et al. (2005) and Hasegawa & Yoshimura (2007) both tested the effects of different degrees of forest canopy cover on commercial grade GPS receivers (Wing et al. used six different types of receivers, Hasegawa & Yoshimura used two SR 530 receivers made by Leica Geosystems). Buczkowski (2016) tested the effects of building shadows on smartphone accuracy, although their testing methods would not satisfy rigorous experimental design.

The conditions that are to be tested are canyons (both steep angle and wide angle), forest canopies and building shadows. In order to test these conditions for this study, benchmark locations have been found in locations that exhibit these different types of conditions, although not completely. Because the conditions needed for accurate survey positions, clear view of the horizon and open sky view to see constellations, are also conditions that are best suited for GPS position fixes the locations to be used only exhibit some of the desired adverse conditions. Meaning tree canopies are not completely covering the sites, and canyons are not as close to the benchmark sites as would be desired. However, additional test sites were added to incorporate more adverse testing conditions. A list of the located benchmarks and other test sites with a description of their adverse conditions are outlined in Table 1 in the methods section.

Chapter 3 Methods

This chapter goes into the specific methods for testing the hypothesis that a BGAN terminal will improve the positional accuracy of an iPhone. The testing uses mainly NGS benchmarks as control point locations, and two easily identifiable historic locations and compares them to all recorded points for determining accuracy. High-resolution satellite images were used to determine the locations of the two historic sites inside an urban environment to test the experiment under significant building shadows. The following chapter is broken up into three sections; the equipment used, the procedures that were followed in the field for data collection, software used and analysis.

3.1. Equipment

Four pieces of equipment were used for this experiment; a set of NGS benchmarks and urban historical sites as control points, a Trimble Geo XH 6000 series GPS receiver, an Apple iPhone 6 loaded with the Fulcrum Data Collection and ArcGIS Collector applications, and a Hughes Inmarsat 9201 BGAN terminal.

3.1.1. NGS Benchmarks & Control Points

In order to have locations with known latitude and longitude coordinates that can be used as control points for collected data, NGS benchmarks were chosen so that they met the criteria as outlined below and were supplemented with identifiable locations that were marked using high resolution satellite images from three separate sources. Benchmarks are surveyed to have positional coordinates accurate to a few millimeters (NOAA 2017) and these coordinates are updated every few years to take into account any land surface shifting. There are nine different types of benchmarks listed on the NGS Data Explorer Interactive Map (National Geodetic

Survey 2017) website which are Continuously Operating Reference Stations (CORS), GPS site, Classic Horizontal, Vertical Control, Approx Height, GPS Vertical Control, GPS Approx Height, Classic Horz and Vert Control, and Classic Horz and Approx Ht. All names are listed as they appear on the NGS interactive map.

Because this study examines horizontal accuracy and not vertical, only points with horizontal accuracy are required, and all benchmarks that only relate to height (Vertical Control and Approx Height) were disregarded. The remaining types of sites were reviewed and visited to determine the best sites for use in this study. CORS are an interesting possibility for control points because the positional information is constantly updated using differential correction. However, using these locations may interfere with the positional testing being conducted by providing an additional signal that would be either a possible source of error or improvement. In order to reduce this possible affect, other NGS benchmark locations were used. Because we are interested in GPS readings, sites listed as GPS sites were chosen to improve the chance of gaining a GPS reading, with two exceptions (see Table 1). Each site presents a different possible source of interference; tree canopy, canyon walls or building shadows, with two sites serving as controls with no discernable source of interference. One control was in a rural area and the other was in an urban setting. These conditions are discussed in more detail in section 3.2.3.

To supplement the NGS benchmarks with areas that were under building shadows, two sites were chosen that were in the middle of downtown San Jose. The Circle of Palms landmark outside the Fairmont Plaza Hotel and the San Jose Museum of Modern Art which has a California Historical Site plaque on its western building. The plaque commemorates the museum as the first post office in the area, which also serves as a control point based on historical location. Both of these landmarks allowed for exact locations to be determined using high-resolution satellite images from three separate sources. Each site was first found on Google Earth Pro and an initial set of coordinates was determined in decimal degrees, or WGS 84. This same process was replicated in both ArcMap with a satellite imagery base map and in Google Maps, although the latter is not the most reliable source; it was acceptable enough to confirm the coordinates determined using the other two methods. To confirm the effectiveness of this process, it was replicated using the other five NGS benchmarks used in the study. The study was able to get the benchmark sites to within one one-hundred-thousandth of a decimal degree using this process. Once the coordinates were determined in WGS 84 they were added to a spreadsheet, imported into ArcMap and then projected to be in California State Plane Zone III for this study.

A total of seven different sites were used for testing; five sites which used NGS benchmarks and two sites that used high-resolution satellite images as described above. Two sites served as controls with no discernable sources of interference and the other five contained some form of interference (what have been termed "adverse conditions" in this report). All sites are located within 2 hours of the San Francisco Bay Area. All sites are located within the California State Plane Zone III to ensure that each set of collected points was projected into the same coordinate system to reduce any errors due to projection. These locations exhibit different types of adverse conditions. They are divided by NGS Benchmarks and satellite determined sites in Table 1. The coordinates for the NGS benchmarks (the first five sites) are listed as they are reported from the NGS website and are in NAD 83 coordinates. While Sites 2, 3 and 4 are designated as "GPS Vertical Control" and "GPS Approx Ht" they do not only list vertical height as sites designated as "Vertical Control" and "Approx Height" do, so were included in this study.

Table 1. Control Point Locations

No.	Site Name	Latitude, Longitude	Established	Last Updated	NGS Control Type	Adverse Condition Notes
1	PASS	37° 04’ 02.53756” N, 121° 12’ 32.79005” W	1943	06/27/12	GPS Site	Control
2	HPGN D CA SAN PEDRO	37° 21’ 14.03975” N, 121° 54’ 25.19341” W	1992	06/27/12	GPS Vertical Control	City Control
3	C 125	37° 20’ 32.59310” N, 121° 42’ 57.62438” W	1976	06/27/12	GPS Vertical Control	Wide Canyon
4	HPGN D CA BELL	37° 02’ 18.86404” N, 121° 18’ 40.03457” W	1992	06/27/12	GPS Approx Ht	Steep Canyon
5	C099	37° 22’ 09.17791” N, 122° 00’ 03.76707” W	1989	06/27/12	GPS Site	Tree Cover
6	Circle Of Palms	37° 20’ 0.384” N, 121° 53’ 24” W	NA	NA	NA	Building Shadow
7	SJ Museum of Art	37° 20’ 0.132” N, 121° 53’ 24” W	NA	NA	NA	Building Shadow

3.1.2. Trimble Geo XH 6000 Series GPS Receiver

A Trimble Geo XH 6000 series GPS receiver was used as test condition 1. This condition serves as the comparison for how efficiently the other test conditions preformed. The Trimble Geo is used in many scientific studies and has a stated accuracy of 1 to 2 meters in ideal conditions and is capable of sub-meter accuracy and even sub-centimeter accuracy when using an antenna with the use of differential correction.

The points generated by the Trimble unit were used as the acceptable accuracy threshold, because these units have an established accuracy that is acceptable for use in scientific studies. Therefore, if the condition of the iPhone paired with a BGAN terminal can achieve consistent accuracy that is comparable to the results obtained by the Trimble receiver then the results will be considered to support the hypothesis.

Collection times were planned with the assistance of the Trimble satellite planning website to ensure the best possible GPS readings were being produced (Trimble 2018). For the time period when the data was collected, satellite placement was looked at cross referenced for the best satellite times and the coolest part of the day. Because the majority of data collection was done in the end of June and the beginning of July, the heat of the day needed to be avoided and collection was done in the evening or in the early morning. Fortunately, those corresponded with the optimal times of satellite coverage. Appendix B shows the different graphs from the Trimble planning site for the day of July 1, 2018 and was indicative of the other collection times.

3.1.3. iPhone 6

The Fulcrum Data Collection (an open access mobile application) and the ArcGIS Collector application (available with an Esri account) were downloaded to the iPhone for use with both the BGAN terminal and without. Both applications use the internal GPS capabilities of the phone. Apple does not provide information relating to the PDOP readings or satellite connections, as this information is considered proprietary by the company. However, using enough sample data will be sufficient to determine how the accuracy changes over the collection time per FGDC guidelines (FGDC 1998). All settings that can improve the GPS position for the iPhone were turned on (Wi-Fi connection and cellular data) to ensure that the only assistance being used in generating a GPS fix with the iPhone was the BGAN terminal. A Wi-Fi connection was not established on the iPhone for Condition 2 even if one was available. This ensured that only the testing conditions using the BGAN terminal were tested with the Wi-Fi connected signal.

3.1.4. BGAN terminal

The BGAN terminal was powered on prior to use, with the iPhone being powered off at this point to ensure no possible contamination of signal. Once the terminal powered on and a signal was acquired, the iPhone was turned on and connected to the Wi-Fi terminal in the BGAN unit then collection began. The BGAN terminal was powered on 2 meters from the control point location to ensure a GPS fix at the first collection distance. A distance of 2 meters was used because it is recommended to stay at least that far away from the terminal due to radiation from the terminal.

3.2. Collection Procedure

The same procedure was followed at all sites for each of the five testing conditions in order to standardize the process.

3.2.1. Setup and Conditions

A tripod stand was used to hold each device (the iPhone and the Trimble receiver) directly over the benchmark. A plumb weight was added to the bottom part of the stand to ensure that the receivers were being placed as close to directly over the benchmark as possible. The stand held the receivers approximately 1 meter in height above the benchmark to simulate a person holding the device. As this study is not interested in altitude readings, the height of the receiver made no difference. Figure 1 shows the stand used with both the iPhone and Trimble receiver.

Figure 1. Tripod set for data collection with Trimble Geo XH 6000 and iPhone.

The condition of the iPhone 6 without the use of the BGAN serves to provide a base from which to see if the use of the BGAN terminal improved that accuracy. During this testing condition the BGAN terminal was powered off and stored in a carry container to ensure no possible contamination could occur.

For the first condition using the BGAN terminal, the terminal was placed 2 meters away from the benchmark in a cardinal direction prior to powering on the terminal and the iPhone. This allowed for a standard positioning of the terminal and no possible influences because of terminal placement. South was originally chosen because the Inmarsat satellites are in geosynchronous orbits around the earth and are situated near the equator, so placing the terminal to the south should provide the best possible connection. But initial field testing showed that the direction could not be standardized due to differences in testing locations. Therefore, the terminal was pointed to face between 137° and 143° South because that was the optimal position designated by the Inmarsat software as having the best chance for signal in the San Jose area. The terminal was kept at an angle of 40° inflection to ensure a signal from the Inmarsat satellites was generated. When the terminal was moved the angle of inflection and the direction it faced were kept the same so that the signal would remain the same, in theory.

The readings from this condition were compared to each of the other conditions to see how the use of the BGAN terminal improved the readings using the iPhone and if that improvement is comparable to the readings from the Trimble receiver. The specific methods such as positioning of the terminal, the number of points to be collected and the sequence of collection is covered in the following section. Table 2 shows the numbered conditions used at each site and what they entail.

Table 2. The conditions used for testing at each site

Condition	GPS Receiver Unit	Distance to BGAN
Condition 1	Trimble Geo HX 6000	N/A
Condition 2	iPhone	N/A
Condition 3	iPhone	2 meters
Condition 4	iPhone	4 meters
Condition 5	iPhone	8 meters

3.2.2. Collection

The collection of each set of points was handled systematically for each condition. Each device was placed into the holding stand and situated over the benchmark, as described above prior to collecting any points. In between Conditions 2, 3, 4 and 5 the iPhone was powered off but remained in the holding stand until the BGAN terminal was positioned and powered on and ready for use. The phone was left on when switching between applications. Each condition collected 20 points for comparison at each site. Per FGDC guidelines, this is the minimal number of points that can be used to gain a comparison of positional accuracy (FGDC 1998).

A data dictionary was created for both the Fulcrum and ArcGIS Collector applications so that the different sets of points could be maintained separately. No data dictionary was created for the Trimble unit and Generic points were used. For the Trimble unit all points were downloaded and transferred to a PC loaded with the Pathfinder software to process the collected data. Each site was corrected using the base station at Mt. Hamilton (which was no more than 50km from any one site) because it was visible at each site being one of the highest points in the area. After post-processing data correction was applied, each file was exported as an Esri shapefile with no projection, as is standard in Pathfinder Office. Breakdowns of all of the different correction statistics from each Trimble collection site are contained in a single table in Appendix A. Once imported into ArcMap, the projection was defined and the data was projected into California State Plane Zone III.

Separate fields were set up in each dictionary to record the site number, the condition type, the trial number and the distance from the BGAN terminal if applicable. A field was also added to record any notes that were of importance. These fields allowed for a more streamed lined process of collection. A separate hand-written notebook was also kept supplementing any unforeseen notes that occurred.

Field testing of the Fulcrum and ArcGIS Collector applications showed that each point had to be collected individually, so the collector had to stand next to the devices while the points were recorded. And while the Trimble receiver does allow for the collection of multiple points that are then averaged together, to keep the collection procedure standardized, individual points were collected using the Trimble receiver allowing no more than four logging intervals to pass.

3.2.3. Distance to BGAN and Adverse Conditions

To test how both distance from the BGAN terminal and different sources of interference affect accuracy using the BGAN terminal, benchmark locations exhibiting different types of interference were found. As indicated earlier, locations that are suitable for highly accurate survey locations are also those needed for highly accurate GPS readings, which posed a minor problem in the methods that was overcome by alternate sites. Sites 1 and 2 served as controls, one in a rural setting and one in an urban setting. This is why they are not listed below as sites exhibiting “adverse conditions.”

The adverse conditions that were looked at are as follows: a location surrounded by wide canyons (slope of 20 – 35 degrees and twenty meters or more from testing site, Site 3), a location surrounded by steep canyons (slope of 35 – 40 degrees and ten meters from the testing site, Site 4), a location underneath a forest canopy (sky coverage of 50% over the site with tree cover on one side, Site 5), and a location in a city with tall buildings (no less than 5 floors, Sites 6 & 7). Figure 2 shows each site that was used for collection with their number and names next to them. Sites 6 and 7 are too close together to be seen as separate points from this scale. The same procedure to test the equipment as outlined above was followed to ensure a standard collection procedure.

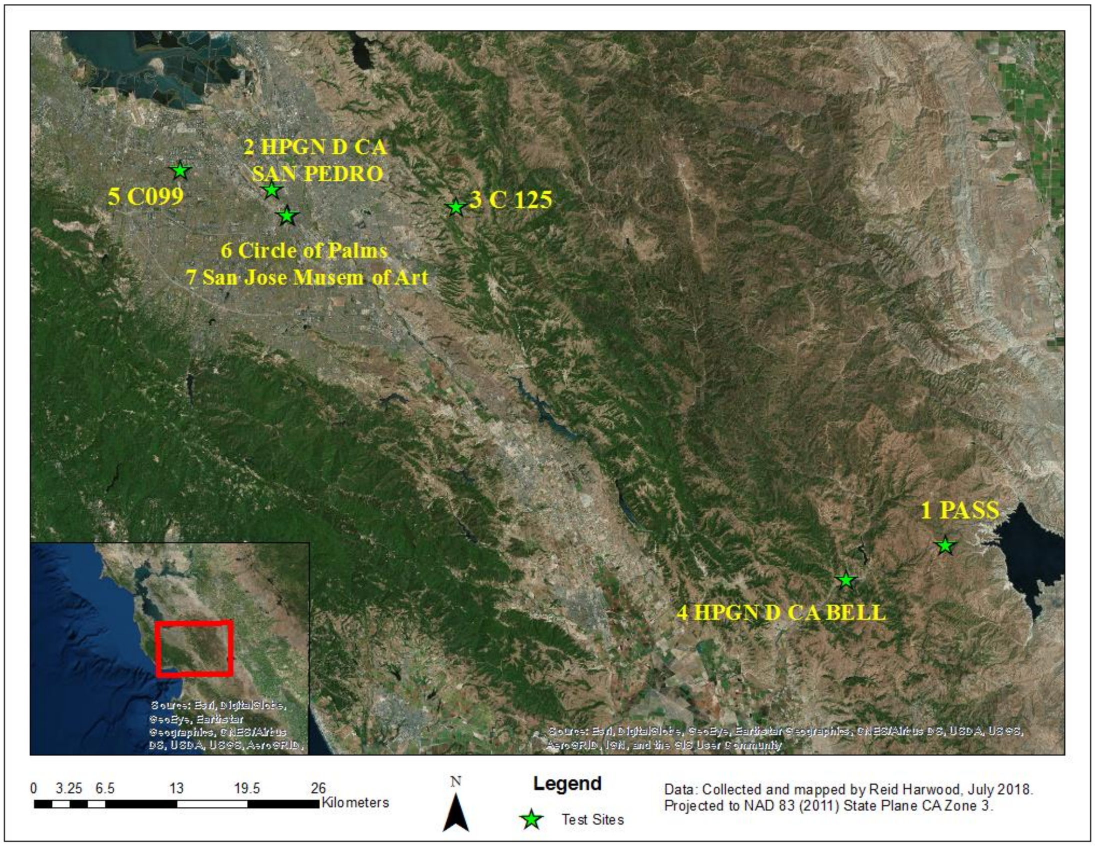


Figure 2. All testing sites used.

The effects of distance between the receiver and BGAN terminal were also tested at each location. For this, the stand holding the receiver remained at the benchmark location and the BGAN terminal was moved away from the site at 2-meter intervals in the same direction. Ideally the same cardinal direction would have been used but some testing locations forced the direction to be different due to environmental factors related to each site. At each distance interval, as determined by a measuring tape, the same procedure of collecting 20 separate points using the iPhone applications was followed. These points were marked as distance measurements with the distance from the BGAN terminal noted in the data dictionary. The distance was increased from 2 meters to 4 meters and then up to 8 meters in distance from the control point locations. Specific directional placement of the BGAN at each site is provided with the results. More distance measurements would have been used but the study was limited by both time and data usage. A direct comparison of accuracy and the improvement gained through connecting to the BGAN is made only among data collected with the iPhone and not the Trimble unit.

3.3. Analysis

Once the points were collected for each day, they were downloaded and saved as separate shape files to keep each day's recordings in the same format. All data were collected in WGS 1984 for both applications on the iPhone and the Trimble Geo XH 6000 unit. The Fulcrum and ArcGIS Collector applications only allow for collection in WGS 1984 so this same coordinate system was used on the Trimble receiver to ensure all measurements were recorded in the same coordinate system. Each set of points was projected to California State Plane Zone III (meters) so that the calculations could be done in planar measurements as directed by the FGDC guidelines (FGDC 1998). The newest versions of each software available was used; ArcMap v. 10.6, Pathfinder v. 5.70, ArcCollector via ArcGIS Online, and Fulcrum Data Collection v. 2.17.0.

3.3.1. Error Calculations

Both the FGDC guidelines and Bolstad (2012) give the same equation for computing error, which is used for our calculations. The equation given for calculating horizontal error is:

$$\text{Accuracy} = \sqrt{(x1 - x0)^2 + (y1 - y0)^2}$$

Where x1 and y1 are the collected coordinate points and x0 and y0 are the coordinate points from the associated benchmark or "check" point as described by the FGDC (1998). The error readings were determined by using the measuring tool in ArcGIS that measures the error in meters by using the projected coordinates and returns a single measurement in meters. This measurement is equal to the calculated error using the above referenced equation. Figure 3 shows a screenshot of the measuring tool in ArcMap that was used to generate the error readings used in the analysis.

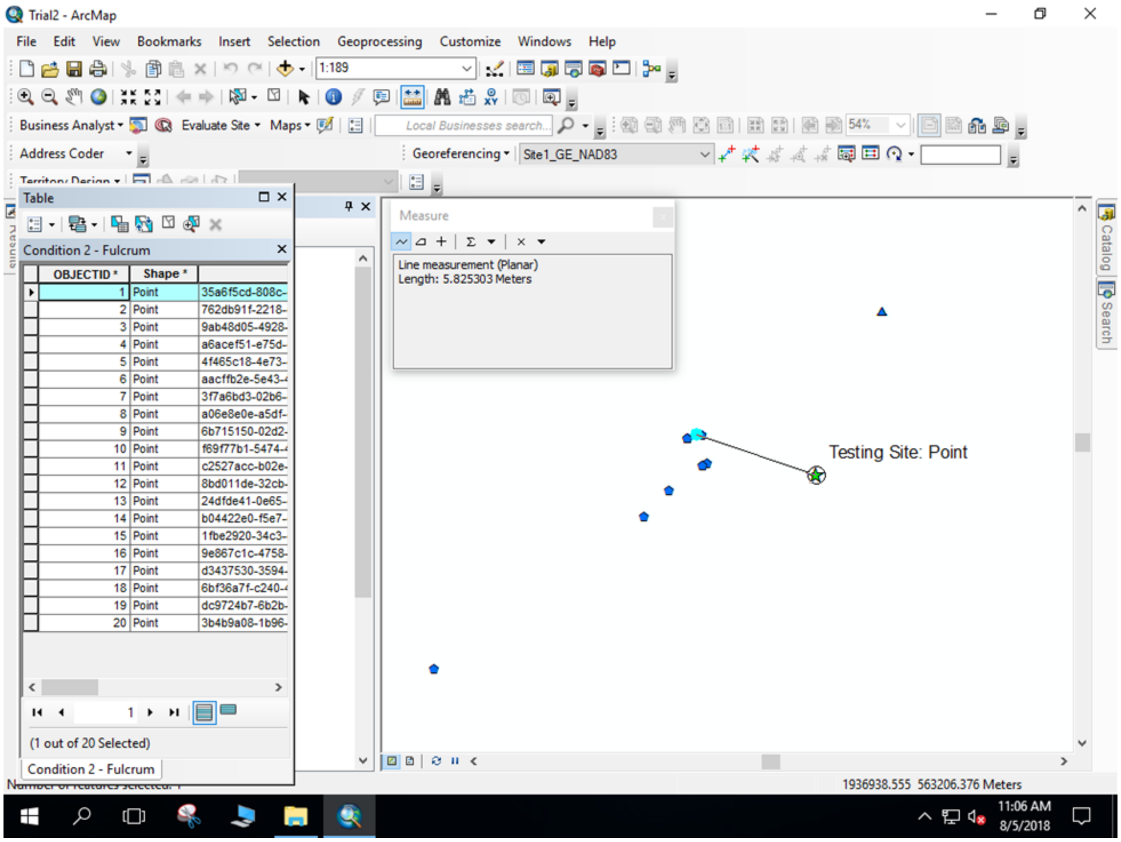


Figure 3. A screenshot of the measure tool in ArcMap which was used to find the error readings used in the analysis.

Once the horizontal error was calculated for each point the root mean square error (RMSE) was calculated as well. The FGDC gives a breakdown of RMSE equations in their Appendix A of the chapter on spatial data accuracy, specifying RMSE for both x and y coordinates as well as the combined horizontal error equation listed above. For the purposes of this study, we will use the equation given as follows:

$$RMSEr = \text{sqrt}[\sum((x1 - x0)^2 + (y1 - y0)^2)/n]$$
$$= \text{sqrt}[(RMSEx)^2 + (RMSEy)^2]$$

Where n is the number of test points collected and the x and y variables are the same as in the horizontal accuracy equation listed above and the lower the RMSEr the more accurate (true to control points) the data collection is. This method required calculating the error for each individual point. Walter and Schultz (2013) also used this error equation with success in determining the error associated with their study. To perform the calculations the error readings were added to a table for each set of points and the calculations were performed in Excel. The ArcGIS suite of programs does compute RMSE, but it appears to be for georeferenced images, line features or polygons. Because of this, the calculations were performed in Excel.

These readings were compared to each other to determine how effective the BGAN terminal was in improving the accuracy of the iPhone and a brief comparison with regards to the accuracy of the Trimble Geo XH 6000. To visually display the error readings multi ring buffers have been included in maps to show how far from each testing site the associated recordings were.

Chapter 4 Findings

After conducting the experiment detailed above, the results show that using a BGAN terminal to improve the positional accuracy of an iPhone is possible but only under certain conditions. The following results are broken down by site and condition. Each testing condition is described in detail, photos of each site are provided for reference and tables showing distance measurements and the calculations for error from the control point site (RMSE). Appendix B shows the satellite availability during the collection times. The optimal times resulted in the Trimble unit being able to access a minimum of eight satellites (GPS only) and possibly as many twenty-two when connections to GLONASS and Galileo satellites were included. This is most likely why the Trimble receiver performed much better than the smartphone, because the smartphone and BGAN terminal only use GPS satellites. Data are visualized for each site to add context to the data.

4.1. Site 1 PASS

The first site used for the experiment is designated as “PASS” on the NGS Interactive Map. It served as a control for the experiment with no discernable sources of interference; it was on top of a hill with no overhead cover, it was in a rural area so no outside signals may have affected the devices, and it was far from any canyon walls improving the site lines between the devices and the satellites. The BGAN terminal was moved to the South for the distance conditions. Figure 4 shows the site photos from Site 1 PASS with a picture of the benchmark and four photos at each cardinal direction to demonstrate what the site looks like. In these photos (as with all the other site photos) the top left image is the view to the north, top right is the view to the south, bottom left is the view to the east and bottom right is the view to the west. Collection was done on June 24, 2018 between six and seven am. Collection time varied slightly but was not a significant difference and therefore was not specifically recorded.

Figure 4. Photos of each cardinal direction at Site 1 and the benchmark.

Figure 5 shows the mapped data points from each experiment for this site. A specific breakdown of each condition follows with the resultant RMSE.

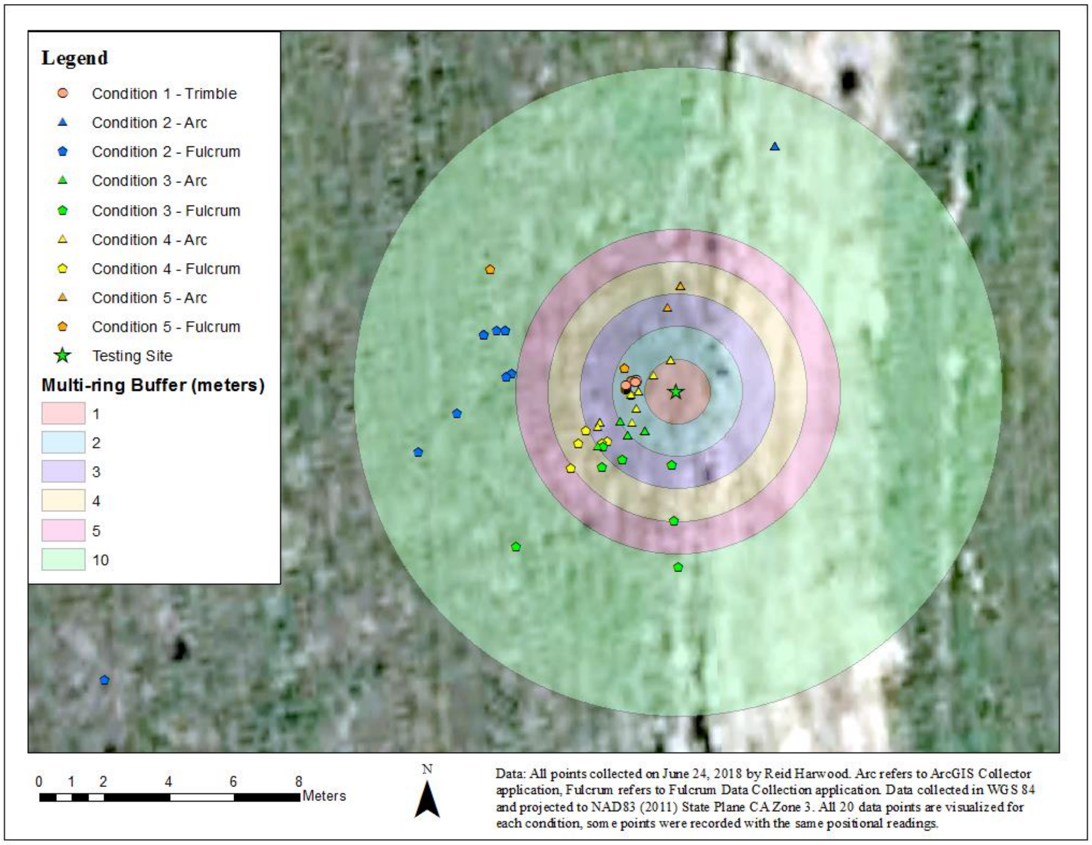


Figure 5. Site 1: Data points for all conditions.

4.1.1. Trimble Geo XH 6000 – Condition 1

As you can see in Figure 5 the Trimble performed as expected, producing results that were within 2 meters of the testing site. Table 3 shows the distances of each data point from the actual control point benchmark and the calculated RMSE of 1.44 meters.

Table 3. Distance Error Measurements from Trimble Data

No.	Measured Error	Error²
1	1.29986	1.68963602
2	1.553864	2.41449333
3	1.550948	2.4054397
4	1.410815	1.99039896
5	1.568179	2.45918538
6	1.543639	2.38282136
7	1.390008	1.93212224
8	1.539285	2.36939831
9	1.543639	2.38282136
10	1.562106	2.44017516
11	1.380104	1.90468705
12	1.386104	1.9212843
13	1.55969	2.4326329
14	1.55969	2.4326329
15	1.3245	1.75430025
16	1.245781	1.5519703
17	1.555793	2.42049186
18	1.264716	1.59950656
19	1.274286	1.62380481
20	1.283142	1.64645339
	AVG	2.08771281
	RMSE	1.44489197

4.1.2. iPhone – Condition 2

The Fulcrum application produced varied results with points scattered at several different distances as can be seen in Figure 5 and Table 4 with a resultant RMSE of 7.30 meters. This may have been better except for one point that was recorded at 20 meters away. The ArcCollector application had only a single position recorded for all 20 points generated, with a RMSE of 8.13 meters. This was most likely due to a malfunction in the phone that caused the application to become “stuck” on a single location. While each application achieved different results, the RMSE were similar to each other and at a distance that was expected for iPhones. Results for each application are reported separately in Table 4 (Fulcrum) and Table 5 (ArcCollector)

Table 4 (left). Distance Error Measurements for Fulcrum Application
Table 5 (right). Distance Error Measurements for ArcCollector Application

No.	Measured Error	Error²
1	5.825303	33.934155
2	5.592503	31.2760898
3	5.592503	31.2760898
4	5.592503	31.2760898
5	5.592503	31.2760898
6	5.592503	31.2760898
7	6.167042	38.032407
8	6.167042	38.032407
9	6.167042	38.032407
10	6.167042	38.032407
11	6.167042	38.032407
12	6.167042	38.032407
13	6.167042	38.032407
14	5.074716	25.7527425
15	5.244316	27.5028503
16	5.244316	27.5028503
17	5.244316	27.5028503
18	6.794024	46.1587621
19	8.157225	66.5403197
20	19.717615	388.784341
	AVG	53.3143085
	RMSE	7.30166478

No.	Measured Error	Error²
1	8.13349	66.1536596
2	8.13349	66.1536596
3	8.13349	66.1536596
4	8.13349	66.1536596
5	8.13349	66.1536596
6	8.13349	66.1536596
7	8.13349	66.1536596
8	8.13349	66.1536596
9	8.13349	66.1536596
10	8.13349	66.1536596
11	8.13349	66.1536596
12	8.13349	66.1536596
13	8.13349	66.1536596
14	8.13349	66.1536596
15	8.13349	66.1536596
16	8.13349	66.1536596
17	8.13349	66.1536596
18	8.13349	66.1536596
19	8.13349	66.1536596
20	8.13349	66.1536596
	AVG	66.1536596
	RMSE	8.13349

4.1.3. iPhone with BGAN at 2 meters – Condition 3

With the assistance of the BGAN terminal, each application was able to improve their positional readings (Figure 5). The Fulcrum application data points ranged in distance from 2.25 to 6.86 meters while the data from the ArcCollector application ranged from 1.57 to 2.95 meters. Improvement of each application and resultant RMSEs are provided in Tables 6 and 7. Both the Fulcrum and ArcCollector applications performed better with the assistance of the BGAN terminal, producing a RMSE of 3.79 and 1.83 respectively.

Table 6 (left). Distance Error Measurements for Fulcrum Application
Table 7 (right). Distance Error Measurements for ArcCollector Application

No.	Measured Error	Error²
1	2.656799	7.05858093
2	2.656799	7.05858093
3	2.656799	7.05858093
4	2.656799	7.05858093
5	2.646799	7.00554495
6	2.815197	7.92533415
7	2.815197	7.92533415
8	3.273841	10.7180349
9	3.273841	10.7180349
10	3.273841	10.7180349
11	2.253961	5.08034019
12	2.253961	5.08034019
13	2.253961	5.08034019
14	2.253961	5.08034019
15	3.963597	15.7101012
16	3.963597	15.7101012
17	5.387658	29.0268587
18	5.387658	29.0268587
19	6.862217	47.0900222
20	6.862217	47.0900222
	AVG	14.3609983
	RMSE	3.78959079

No.	Measured Error	Error²
1	2.952348	8.71635871
2	2.010108	4.04053417
3	2.010108	4.04053417
4	2.010108	4.04053417
5	2.010108	4.04053417
6	2.010108	4.04053417
7	1.566716	2.45459902
8	1.566716	2.45459902
9	1.566716	2.45459902
10	1.566716	2.45459902
11	1.566716	2.45459902
12	1.566716	2.45459902
13	1.566716	2.45459902
14	1.566716	2.45459902
15	1.566716	2.45459902
16	1.566716	2.45459902
17	1.566716	2.45459902
18	1.946185	3.78763605
19	1.946185	3.78763605
20	1.946185	3.78763605
	AVG	3.36412635
	RMSE	1.83415549

4.1.4. iPhone with BGAN at 4 meters – Condition 4

Moving the BGAN terminal to 4 meters had a minor effect on the positional readings of the iPhone but not at the rate it had between Conditions 2 and 3. With the BGAN at a distance of 4 meters the positional readings were improved for both applications, but each RMSE decreased by less than a single meter. The data from the Fulcrum application ranged from 1.38 meters to 4.01 meters and resulted in a RMSE of 3.33 meters, less than half a meter improvement. The ArcCollector application data ranged from 0.99 meters to 2.66 meters and resulted in a RMSE of 1.78 meters, barely a tenth of a meter improvement. While changing the distance from 2 meters to 4 meters did have an effect on the positional readings of the iPhone, it does not seem to be large enough to say there was a meaningful effect from distance. Results for each application are reported separately in Table 8 (Fulcrum) and Table 9 (ArcCollector).

Table 8 (left). Distance Error Measurements for Fulcrum Application
Table 9 (right). Distance Error Measurements for ArcColelctor Application

No.	Measured Error	Error²
1	1.378492	1.90024019
2	3.405243	11.5956799
3	3.405243	11.5956799
4	3.405243	11.5956799
5	3.405243	11.5956799
6	3.405243	11.5956799
7	3.004541	9.02726662
8	3.004541	9.02726662
9	3.004541	9.02726662
10	3.004541	9.02726662
11	4.006736	16.0539334
12	4.006736	16.0539334
13	4.006736	16.0539334
14	4.006736	16.0539334
15	4.006736	16.0539334
16	4.006736	16.0539334
17	2.612684	6.82611768
18	2.612684	6.82611768
19	2.774952	7.7003586
20	2.774952	7.7003586
	AVG	11.0682129
	RMSE	3.32689239

No.	Measured Error	Error²
1	1.378393	1.89996726
2	0.986696	0.973569
3	0.986696	0.973569
4	0.986696	0.973569
5	0.986696	0.973569
6	0.843498	0.71148888
7	1.142004	1.30417314
8	1.142004	1.30417314
9	1.142004	1.30417314
10	1.142004	1.30417314
11	1.31749	1.7357799
12	1.31749	1.7357799
13	1.678756	2.81822171
14	2.536439	6.4335228
15	2.536439	6.4335228
16	2.536439	6.4335228
17	2.536439	6.4335228
18	2.536439	6.4335228
19	2.536439	6.4335228
20	2.658461	7.06741489
	AVG	3.18403789
	RMSE	1.78438726

4.1.5. iPhone with BGAN at 8 meters – Condition 5

Moving the BGAN terminal to 8 meters form the testing site still had an effect on the positional readings but not as much as the previous two conditions using the BGAN terminal. The terminal was still unobstructed from any overhead cover but was just farther from the testing site. With the data collection taking place at 8 meters from the BGAN, the positional accuracy of the iPhone was less than when at 2 meters and 4 meters from the BGAN, with a RMSE of 4.02 meters for the Fulcrum application and 3.19 for the ArcCollector application. While the accuracy in this test condition for both the Fulcrum and ArcCollector applications decreased as compared to other BGAN readings, it was still an improvement when compared to the original iPhone condition without the assistance of the BGAN terminal (Condition 2). Results for each application are reported separately in Table 10 (Fulcrum) and Table 11 (ArcCollector).

Table 10 (left). Distance Error Measurements for Fulcrum Application
Table 11 (right). Distance Error Measurements for ArcCollector Application

No.	Measured Error	Error²
1	6.84876	46.9055135
2	6.84876	46.9055135
3	6.84876	46.9055135
4	6.84876	46.9055135
5	6.84876	46.9055135
6	6.84876	46.9055135
7	1.736081	3.01397724
8	1.736081	3.01397724
9	1.736081	3.01397724
10	1.736081	3.01397724
11	1.736081	3.01397724
12	1.736081	3.01397724
13	1.736081	3.01397724
14	1.736081	3.01397724
15	1.736081	3.01397724
16	1.736081	3.01397724
17	1.736081	3.01397724
18	1.736081	3.01397724
19	1.736081	3.01397724
20	1.736081	3.01397724
	AVG	16.1814381
	RMSE	4.02261583

No.	Measured Error	Error²
1	3.252751	10.5803891
2	3.252751	10.5803891
3	3.252751	10.5803891
4	3.252751	10.5803891
5	3.252751	10.5803891
6	3.252751	10.5803891
7	3.252751	10.5803891
8	3.252751	10.5803891
9	3.252751	10.5803891
10	3.252751	10.5803891
11	3.252751	10.5803891
12	3.252751	10.5803891
13	3.252751	10.5803891
14	3.252751	10.5803891
15	3.252751	10.5803891
16	3.252751	10.5803891
17	3.252751	10.5803891
18	3.252751	10.5803891
19	2.580776	6.66040476
20	2.580776	6.66040476
	AVG	10.1883906
	RMSE	3.19192585

The results of Site 1 show that the use of a BGAN terminal does have the ability to improve the positional accuracy of an iPhone. The optimal distance for collection and how other conditions affect this are shown through the other testing sites and in Chapter 5.

4.2. Site 2 HPGN D CA SAN PEDRO

The second site tested was an urban area with limited adverse conditions that would serve as the "urban" control point. This site was within city limits but about 1 kilometer from the nearest buildings to minimize the effects of building shadows. The BGAN terminal was moved to the north for distance testing so that it would not be blocked by the shadow of the storage container to the south. Collection occurred on July 1, 2018 and started at six am. Figure 6 shows the site photos from Site 2 HPGN D CA SAN PEDRO with a picture of the benchmark and four photos in each of the cardinal directions.

Figure 6. Photos of each cardinal direction at Site 2 and the benchmark.

As you can see, the site is free of obstructions near the site but does have buildings in the distance that may potentially interfere with line of site to satellites nearer the horizon, as opposed to Site 1. Figure 7 shows the mapped data points collected for each testing condition for this site. A specific breakdown of each condition follows with the resultant RMSE.

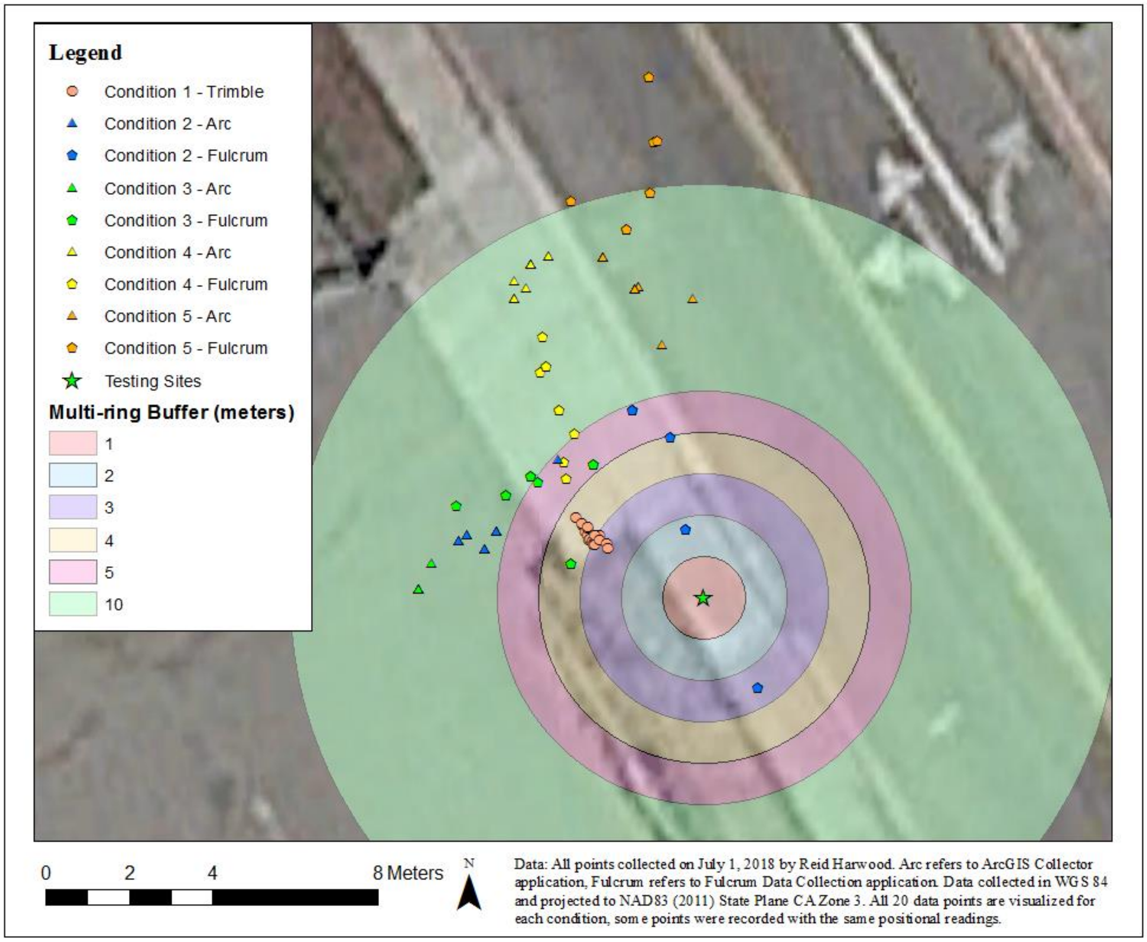


Figure 7. Site 2: Data points for all conditions.

4.2.1. Trimble Geo XH 6000 – Condition 1

The Trimble unit produced results that were clustered together at a distance of about 3 meters, with none exceeding 4 meters in distance from the testing site. As Figure 7 shows, the Trimble unit collected the most uniform points, with all data concentrated in the same area and resultant RMSE of 3.10 meters. These results are a little larger in error than would be expected of such a high sensitivity device, ranging from 2.60 meters to 3.65 meters. The measured distance error of each point and calculated RMSE for this condition are in Table 12.

Table 12. Distance Error Measurements from Trimble Data

No.	Measured Er	Error²
1	2.933012	8.60255939
2	3.372814	11.3758743
3	3.649637	13.3198502
4	3.450243	11.9041768
5	3.261045	10.6344145
6	3.177873	10.0988768
7	3.100275	9.61170508
8	3.084652	9.51507796
9	3.0196	9.11798416
10	2.962255	8.77495469
11	2.937588	8.62942326
12	2.914685	8.49538865
13	3.269382	10.6888587
14	3.274174	10.7202154
15	3.026223	9.15802565
16	2.875872	8.27063976
17	2.674617	7.1535761
18	2.5971	6.74492841
19	3.177873	10.0988768
20	3.0196	9.11798416
	AVG	9.60166953
	RMSE	3.09865609

4.2.2. iPhone – Condition 2

Several of the data points collected with both the Fulcrum application and the ArcCollector application had the same positional locations, similar to the results form Site 1. While the ArcCollector application did record more than one position, several overlapped each other. The Fulcrum application also recorded several points with the same positional locations, as can be seen in Figure 7 and Table 13. Interestingly, the RMSE values for both applications were lower at this site than at Site 1 for Condition 2, with the Fulcrum application data ranging from 1.72 meters to 4.85 meters and producing a RMSE of 3.87. The ArcCollector application data ranged from 4.83 meters to 6.07 meters, producing a RMSE of 5.48 at this site. Results for each application are reported separately in the Table 13 (Fulcrum) and Table 14 (ArcCollector).

Table 13 (left). Distance Error Measurements for Fulcrum Application
Table 14 (right). Distance Error Measurements for ArcCollector Application

No.	Measured Error	Error²
1	2.531486	6.40842137
2	2.531486	6.40842137
3	2.531486	6.40842137
4	1.715382	2.94253541
5	1.715382	2.94253541
6	1.715382	2.94253541
7	1.715382	2.94253541
8	1.715382	2.94253541
9	3.956335	15.6525866
10	3.956335	15.6525866
11	4.848219	23.5052275
12	4.848219	23.5052275
13	4.848219	23.5052275
14	4.848249	23.5055184
15	4.848249	23.5055184
16	4.848249	23.5055184
17	4.848249	23.5055184
18	4.848249	23.5055184
19	4.848249	23.5055184
20	4.848249	23.5055184
	AVG	15.0148713
	RMSE	3.87490274

No.	Measured Error	Error²
1	4.829957	23.3284846
2	5.229434	27.34698
3	5.229434	27.34698
4	5.229434	27.34698
5	5.229434	27.34698
6	5.229434	27.34698
7	5.229434	27.34698
8	5.229434	27.34698
9	5.229434	27.34698
10	5.229434	27.34698
11	5.415324	29.325734
12	5.415324	29.325734
13	5.415324	29.325734
14	5.415324	29.325734
15	5.891326	34.707722
16	5.891326	34.707722
17	5.891326	34.707722
18	6.072213	36.8717707
19	6.072213	36.8717707
20	6.072213	36.8717707
	AVG	30.0746359
	RMSE	5.48403464

4.2.3. iPhone with BGAN at 2 meters – Condition 3

After seeing the results from Site 1, one would expect that the use of the BGAN terminal would have the same effect at this site as well but that was not the case. Both applications returned results that were of a higher error reading than Condition 2 for this site. The Fulcrum application data ranged from 3.30 meters to 6.37 meters and resultant RMSE of 4.49 meters and the ArcCollector application data ranged from 6.61 meters to 6.88 meters with a resultant RMSE of 6.87 meters. These results are within a meter of difference from the results of Condition 2 but in the opposite direction than expected. This condition also produced duplicate positional readings from both applications, which must have been a product of the iPhone. Results for each application are reported separately in Table 15 (Fulcrum) and Table 16 (ArcCollector).

Table 15 (left). Distance Error Measurements for Fulcrum Application
Table 16 (right). Distance Error Measurements for ArcCollector Application

No.	Measured Error	Error²
1	6.369831	40.574747
2	5.384004	28.9874991
3	5.384004	28.9874991
4	5.384004	28.9874991
5	4.8878825	23.8913953
6	5.09591	25.9682987
7	5.09591	25.9682987
8	5.09591	25.9682987
9	5.09591	25.9682987
10	5.09591	25.9682987
11	3.296205	10.8649674
12	3.296205	10.8649674
13	3.296205	10.8649674
14	3.296205	10.8649674
15	3.296205	10.8649674
16	3.296205	10.8649674
17	3.296205	10.8649674
18	3.296205	10.8649674
19	4.184804	17.5125845
20	4.184804	17.5125845
	AVG	20.1607521
	RMSE	4.49007261

No.	Measured Error	Error²
1	6.613384	43.7368479
2	6.879105	47.3220856
3	6.879105	47.3220856
4	6.879105	47.3220856
5	6.879105	47.3220856
6	6.879105	47.3220856
7	6.879105	47.3220856
8	6.879105	47.3220856
9	6.879105	47.3220856
10	6.879105	47.3220856
11	6.879105	47.3220856
12	6.879105	47.3220856
13	6.879105	47.3220856
14	6.879105	47.3220856
15	6.879105	47.3220856
16	6.879105	47.3220856
17	6.879105	47.3220856
18	6.879105	47.3220856
19	6.879105	47.3220856
20	6.879105	47.3220856
	AVG	47.1428237
	RMSE	6.86606319

4.2.4. iPhone with BGAN at 4 meters – Condition 4

The results from this condition followed the same pattern as was seen between conditions 2 and 3 but with a more pronounced effect. Both applications produced RMSE that were higher than the initial readings from both Conditions 2 and 3. The Fulcrum application data ranged from 4.18 meters to 7.41 meters with a resultant RMSE of 5.52 meters and the ArcCollector application data ranged from 8.55 meters to 9.08 meters with a resultant RMSE of 8.94 meters. The map in Figure 7 shows just how different the readings from Conditions 3 and 4 were in positions, as Condition 4 from both applications disperse to the North of the site and are not as clustered as the results from Conditions 2 and 3. Results for each application are reported separately in Table 17 (Fulcrum) and Table 18 (ArcCollector).

Table 17 (left). Distance Error Measurements for Fulcrum Application
Table 18 (right). Distance Error Measurements for ArcCollector Application

No.	Measured Error	Error²
1	4.184804	17.5125845
2	4.184804	17.5125845
3	4.184804	17.5125845
4	4.184804	17.5125845
5	4.184804	17.5125845
6	4.383704	19.2168608
7	4.383704	19.2168608
8	4.714603	22.2274814
9	4.714603	22.2274814
10	5.043549	25.4373865
11	5.708826	32.5906943
12	5.708826	32.5906943
13	5.708826	32.5906943
14	5.708826	32.5906943
15	6.714113	45.0793134
16	6.755531	45.6371991
17	6.755531	45.6371991
18	6.755531	45.6371991
19	6.755531	45.6371991
20	7.409703	54.9036985
	AVG	30.439179
	RMSE	5.51717128

No.	Measured Error	Error²
1	8.550225	73.1063476
2	8.550225	73.1063476
3	8.550225	73.1063476
4	8.550225	73.1063476
5	8.618393	74.2766979
6	9.077417	82.3994994
7	9.077417	82.3994994
8	9.077417	82.3994994
9	9.077417	82.3994994
10	9.077417	82.3994994
11	9.077417	82.3994994
12	9.077417	82.3994994
13	9.077417	82.3994994
14	9.077417	82.3994994
15	9.077417	82.3994994
16	9.077417	82.3994994
17	9.077417	82.3994994
18	8.927286	79.6964353
19	9.043293	81.7811483
20	9.043293	81.7811483
	AVG	79.9377406
	RMSE	8.94079083

Several things are interesting about these findings, mainly the difference in how each application responded to the changes created by the BGAN. One would expect that both applications would have similar results in how affected they were in recording positional accuracy, but that does not seem to be the case. It is also surprising that the Fulcrum application out preformed the ArcCollector application at this site, because as we will see the ArcCollector application produced more reliable results for many of the other sites.

4.2.5. iPhone with BGAN at 8 meters – Condition 5

After increasing the distance of the BGAN from the testing site, the applications continued to perform in an unexpected manner. At a distance of 8 meters, each application had a different result in determining accuracy. The Fulcrum application almost doubled the error readings, with a resultant RMSE of 10.37 and points ranging from 9.09 meters to 12.65 meters, while the ArcCollector application improved with a resultant RMSE of 7.94 and points ranging from 6.18 meters to 8.56 meters. Results for each application are reported separately in Table 19 (Fulcrum) and Table 20 (ArcCollector).

Table 19 (left). Distance Error Measurements for Fulcrum Application
Table 20 (right). Distance Error Measurements for ArcCollector Application

No.	Measured Error	Error²
1	10.096839	101.946158
2	9.095598	82.729903
3	9.095598	82.729903
4	9.095598	82.729903
5	9.095598	82.729903
6	9.095598	82.729903
7	9.095598	82.729903
8	9.095598	82.729903
9	9.875696	97.5293715
10	9.875696	97.5293715
11	9.875696	97.5293715
12	9.875696	97.5293715
13	9.875696	97.5293715
14	9.875696	97.5293715
15	11.075641	122.669824
16	11.075641	122.669824
17	12.649559	160.011343
18	12.649559	160.011343
19	12.649559	160.011343
20	12.649559	160.011343
	AVG	107.580836
	RMSE	10.3721182

No.	Measured Error	Error²
1	6.179405	38.1850462
2	7.215546	52.0641041
3	7.677882	58.949872
4	7.677882	58.949872
5	7.677882	58.949872
6	7.640555	58.3780807
7	7.640555	58.3780807
8	7.640555	58.3780807
9	7.640555	58.3780807
10	7.640555	58.3780807
11	7.640555	58.3780807
12	7.640555	58.3780807
13	8.562428	73.3151733
14	8.562428	73.3151733
15	8.562428	73.3151733
16	8.562428	73.3151733
17	8.562428	73.3151733
18	8.562428	73.3151733
19	8.562428	73.3151733
20	8.562428	73.3151733
	AVG	63.1133359
	RMSE	7.94439021

The ArcCollector data is still similar to what the other readings had been, but it is the Fulcrum data resulting in a RMSE that is almost double the one returned for Condition 4 that is most surprising. Something must have affected to Fulcrum application causing it to get positional readings that were very different from not only the ArcCollector application but also from the pattern of the other Fulcrum data at other sites.

4.3. Site 3 C125

Site 3 was a “canyon” condition and as such was located in a wide-angle canyon with hills about .5 kilometer from the site at a slope of about 30°. The canyon is a long valley to the east of San Jose with Joseph D. Grant County Park located there. No cell signal was acquired at the site and thus it provided a good vacuum for using the BGAN terminal. The BGAN terminal was moved to the east for distance conditions. Collection occurred on July 1, 2018 starting at eight am. Figure 8 shows the site photos, with one picture of the benchmark and four others in each cardinal direction, the canyon wall is apparent in the east and west photos.

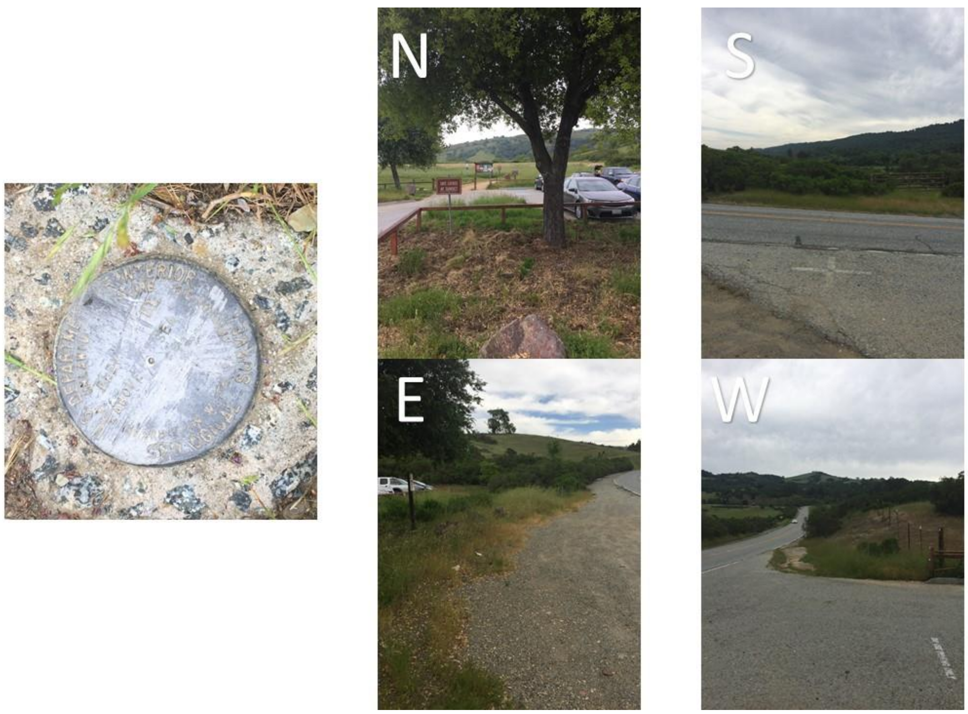


Figure 8. Photos of each cardinal direction at Site 3 and the benchmark.

Figure 9 shows the mapped data points collected for each testing condition for this site. A specific breakdown of each condition follows with the resultant RMSE.

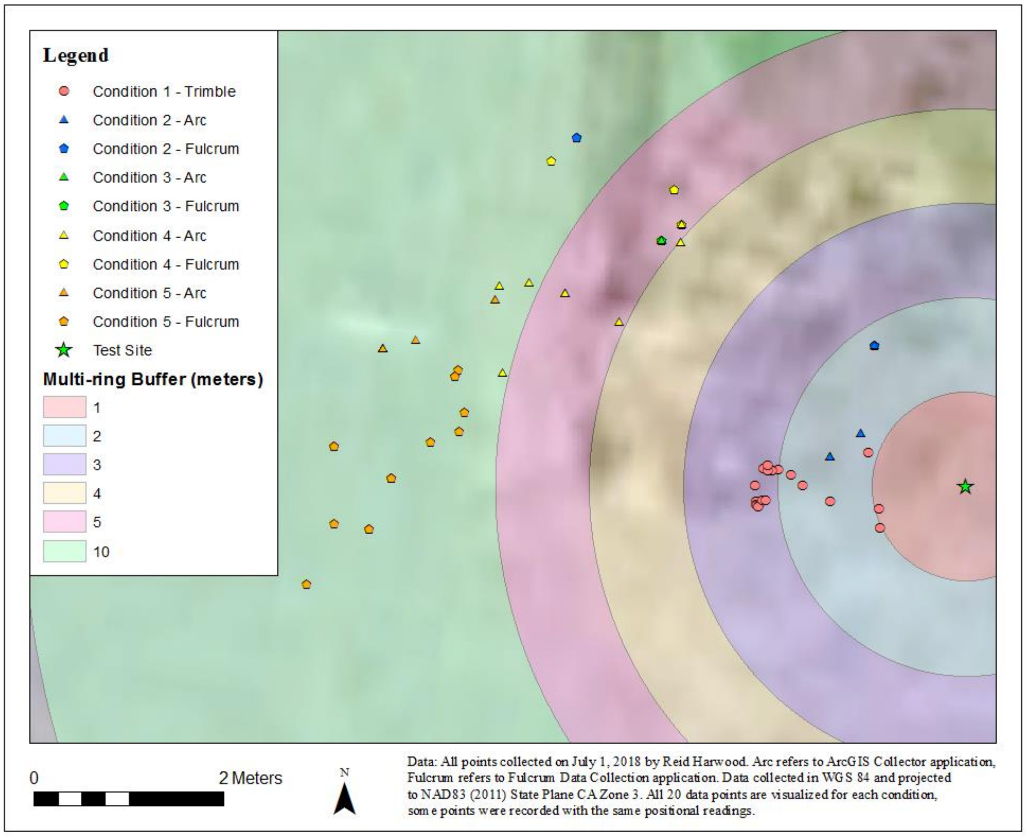


Figure 9. Site 3: Data points for all conditions.

4.3.1. Trimble Geo XH 6000 – Condition 1

As can be seen in Figure 9, the Trimble unit preformed as expected. The majority of the points are concentrated together about 2 meters from the testing site. There is more variation than originally expected, with accuracies ranging from 0.97 to 2.25 meters and the RMSE of 1.97 meters is larger than what was expected. Results for the recorded data are reported in Table 21.

Table 21. Distance Error Measurements from Trimble Data

No.	Measured Error	Error²
1	1.110911	1.23412325
2	0.972012	0.94480733
3	1.023952	1.0484777
4	1.465829	2.14865466
5	1.755036	3.08015136
6	1.884171	3.55010036
7	2.017955	4.07214238
8	2.122923	4.50680206
9	2.171264	4.71438736
10	2.11802	4.48600872
11	2.084259	4.34413558
12	2.129494	4.5347447
13	2.131327	4.54255478
14	2.254854	5.08436656
15	2.256062	5.08981575
16	2.253125	5.07657227
17	2.241108	5.02256507
18	2.222596	4.93993298
19	2.228438	4.96593592
20	2.149999	4.6224957
	AVG	3.90043872
	RMSE	1.97495284

4.3.2. iPhone – Condition 2

For this condition, both applications recorded only a few separate positions for all 20 data points collected, two from the Fulcrum application and three from the ArcCollector application. Figure 6 displays them as the dark blue pentagons and triangles, respectively. The ArcCollector application performed better with data points ranging from 1.26 meters to 1.79 meters and a RMSE of 1.47 meters compared to data points ranging from 1.79 meters to 5.55 meters and a resultant RMSE of 3.39 meters from the Fulcrum application. Results for each application are reported separately in Table 22 (Fulcrum) and Table 23 (ArcCollector).

Table 22 (left). Distance Error Measurements for Fulcrum Application
Table 23 (right). Distance Error Measurements for ArcCollector Application

No.	Measured Error	Error²
1	5.550996	30.8135566
2	5.550996	30.8135566
3	5.550996	30.8135566
4	5.550996	30.8135566
5	5.550996	30.8135566
6	5.550996	30.8135566
7	1.793819	3.2177866
8	1.793819	3.2177866
9	1.793819	3.2177866
10	1.793819	3.2177866
11	1.793819	3.2177866
12	1.793819	3.2177866
13	1.793819	3.2177866
14	1.793819	3.2177866
15	1.793819	3.2177866
16	1.793819	3.2177866
17	1.793819	3.2177866
18	1.793819	3.2177866
19	1.793819	3.2177866
20	1.793819	3.2177866
	AVG	11.4965176
	RMSE	3.3906515

No.	Measured Error	Error²
1	1.793819	3.2177866
2	1.265481	1.60144216
3	1.265481	1.60144216
4	1.265481	1.60144216
5	1.265481	1.60144216
6	1.490182	2.22064239
7	1.490182	2.22064239
8	1.490182	2.22064239
9	1.490182	2.22064239
10	1.490182	2.22064239
11	1.490182	2.22064239
12	1.490182	2.22064239
13	1.490182	2.22064239
14	1.490182	2.22064239
15	1.490182	2.22064239
16	1.490182	2.22064239
17	1.490182	2.22064239
18	1.490182	2.22064239
19	1.490182	2.22064239
20	1.490182	2.22064239
	AVG	2.14665956
	RMSE	1.46514831

4.3.3. iPhone with BGAN at 2 meters – Condition 3

This condition produced similar results as Condition 2 even with the BGAN terminal moved to the East. Both applications only recorded one position for all 20 points and each application recorded them at nearly the same positional location. This is why Figure 9 only shows a single position for both Condition 3s and why the Fulcrum pentagon is barely visible, as it is behind the ArcCollector triangle. The resultant RMSE for the both applications was 4.16 meters. Results for each application are reported separately in Table 24 (Fulcrum) and Table 25 (ArcCollector). As described in the methods section, each point was selected and measured individually to the test site to ensure any variations in positions would be recorded. For this condition, every point was located in almost the same position but still measured individually.

Table 24 (left). Distance Error Measurements for Fulcrum Application
Table 25 (right). Distance Error Measurements for ArcCollector Application

No.	Measured Error	Error²
1	4.159378	17.3004253
2	4.159378	17.3004253
3	4.159378	17.3004253
4	4.159378	17.3004253
5	4.159378	17.3004253
6	4.159378	17.3004253
7	4.159378	17.3004253
8	4.159378	17.3004253
9	4.159378	17.3004253
10	4.159378	17.3004253
11	4.159378	17.3004253
12	4.159378	17.3004253
13	4.159378	17.3004253
14	4.159378	17.3004253
15	4.159378	17.3004253
16	4.159378	17.3004253
17	4.159378	17.3004253
18	4.159378	17.3004253
19	4.159378	17.3004253
20	4.159378	17.3004253
	AVG	17.3004253
	RMSE	4.159378

No.	Measured Error	Error²
1	4.159441	17.3009494
2	4.159441	17.3009494
3	4.159441	17.3009494
4	4.159441	17.3009494
5	4.159441	17.3009494
6	4.159441	17.3009494
7	4.159441	17.3009494
8	4.159441	17.3009494
9	4.159441	17.3009494
10	4.159441	17.3009494
11	4.159441	17.3009494
12	4.159441	17.3009494
13	4.159441	17.3009494
14	4.159441	17.3009494
15	4.159441	17.3009494
16	4.159441	17.3009494
17	4.159441	17.3009494
18	4.159441	17.3009494
19	4.159441	17.3009494
20	4.159441	17.3009494
	AVG	17.3009494
	RMSE	4.159441

4.3.4. iPhone with BGAN at 4 meters – Condition 4

At a distance of 4 meters from the testing site, both applications still experienced the same happenstance of recording multiple data points with the same positions. There was more variation in this condition as to how many locations were recorded, but not as many was would be expected. The Fulcrum and ArcCollector applications recorded a RMSE of 4.43 and 4.61 meters respectively, with the Fulcrum data points ranging from 4.11 meters to 5.60 meters and the ArcCollector data points ranging from 3.99 meters to 5.40 meters. Results for each application are reported separately in Table 26 (Fulcrum) and Table 27 (ArcCollector).

Table 26 (left). Distance Error Measurements for Fulcrum Application
Table 27 (right). Distance Error Measurements for ArcCollector Application

No.	Measured Error	Error²
1	5.597069	31.3271814
2	4.418519	19.5233102
3	4.418519	19.5233102
4	4.418519	19.5233102
5	4.418519	19.5233102
6	4.418519	19.5233102
7	4.418519	19.5233102
8	4.418519	19.5233102
9	4.418519	19.5233102
10	4.418519	19.5233102
11	4.418519	19.5233102
12	4.418519	19.5233102
13	4.418519	19.5233102
14	4.418519	19.5233102
15	4.418519	19.5233102
16	4.418519	19.5233102
17	4.116029	16.9416947
18	4.116029	16.9416947
19	4.116029	16.9416947
20	4.116029	16.9416947
	AVG	19.5971806
	RMSE	4.4268703

No.	Measured Error	Error²
1	4.15955	17.3018562
2	4.115955	16.9410856
3	4.115955	16.9410856
4	3.997275	15.9782074
5	3.997275	15.9782074
6	3.997275	15.9782074
7	4.086717	16.7012558
8	4.086717	16.7012558
9	4.728665	22.3602727
10	4.728665	22.3602727
11	4.728665	22.3602727
12	4.728665	22.3602727
13	4.728665	22.3602727
14	4.728665	22.3602727
15	4.728665	22.3602727
16	5.124478	26.2602748
17	5.124478	26.2602748
18	5.396209	29.1190716
19	5.396209	29.1190716
20	5.07117	25.7167652
	AVG	21.2759264
	RMSE	4.61258348

4.3.5. iPhone with BGAN at 8 meters – Condition 5

Condition 5 at this site showed a result that was expected, a continued reduction in accuracy from both the 2 meter and 4 meter conditions. The Fulcrum application data ranged from 5.39 meters to 7.07 meters and produced a RMSE of 6.22 meters, and the ArcCollector application data ranged from 5.07 meters to 6.36 meters and produced a RMSE of 6.20 meters. Results for each application are reported separately in Table 28 (Fulcrum) and Table 29 (ArcCollector). It is also interesting that both applications at this distance recorded a larger variation in point locations than at any other distance for this test site, even without the BGAN terminal.

Table 28 (left). Distance Error Measurements for Fulcrum Application
Table 29 (right). Distance Error Measurements for ArcCollector Application

No.	Measured Error	Error²
1	5.419979	29.3761724
2	6.100737	37.2189919
3	6.100737	37.2189919
4	6.100737	37.2189919
5	6.100737	37.2189919
6	6.100737	37.2189919
7	6.100737	37.2189919
8	6.360049	40.4502233
9	6.360049	40.4502233
10	6.360049	40.4502233
11	7.072989	50.0271734
12	6.726362	45.2439458
13	6.726052	45.2397755
14	6.726052	45.2397755
15	6.726052	45.2397755
16	6.726052	45.2397755
17	5.541188	30.7047645
18	5.391182	29.0648434
19	5.714113	32.6510874
20	5.556945	30.8796377
	AVG	38.6785674
	RMSE	6.21920955

No.	Measured Error	Error²
1	5.07117	25.7167652
2	5.384396	28.9917203
3	5.384396	28.9917203
4	6.053171	36.6408792
5	6.3632	40.4903142
6	6.3632	40.4903142
7	6.3632	40.4903142
8	6.3632	40.4903142
9	6.3632	40.4903142
10	6.3632	40.4903142
11	6.3632	40.4903142
12	6.3632	40.4903142
13	6.3632	40.4903142
14	6.3632	40.4903142
15	6.3632	40.4903142
16	6.3632	40.4903142
17	6.3632	40.4903142
18	6.3632	40.4903142
19	6.3632	40.4903142
20	6.3632	40.4903142
	AVG	38.4093056
	RMSE	6.19752415

4.4. Site 4 HPGN D CA BELL

Site 4 also represents the "canyon" condition, but this canyon was much steeper and the hills much closer to the testing site than Site 3 (Figure 10, photos north and south). The canyon walls were closer than Site 3 because the benchmark was located part way up the slope of a hill that was at about a 45° angle. This canyon runs east to west and has CA Highway 152 running through it and the benchmark on the north side of the highway. The BGAN terminal was moved to the south for distance testing, away from the nearest canyon wall. Collection occurred on June 24, 2018 starting at eight am. Figure 8 shows the site photos with a picture of the benchmark and four pictures of each cardinal direction.

Figure 10. Photos of each cardinal direction at Site 4 and the benchmark..

The results from this site covered such a large area that two maps are provided for reference at two different scales. Figure 11 is the larger scale map that shows the majority of points collected, while Figure 12 is the smaller scale map that includes the data points from Fulcrum - Condition 5. Why these points ended up being so far away from the test site is unknown and possibilities are discussed in Chapter 5.

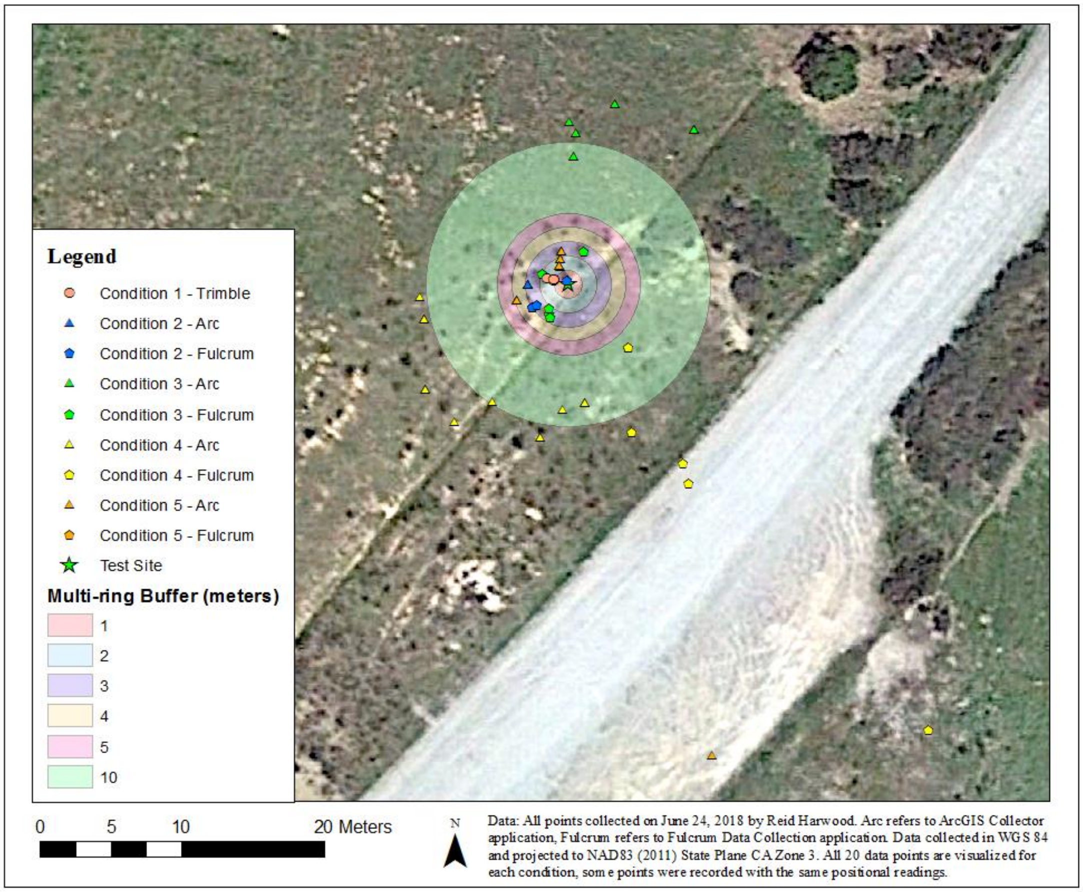


Figure 11. Site 4: Data points for all conditions, except Fulcrum Condition 5.

(Intentionally Left Blank)

Figure 12. Site 4: Data points for all conditions.

4.4.1. Trimble Geo XH 6000 – Condition 1

The Trimble receiver again performed as expected, returning results that were around 1 meter from the test site and clustered together, ranging from 1.04 meters to 1.57 meters. Table 30 shows the distances of each data point from the actual control point benchmark and the calculated RMSE of 1.10 meters.

Table 30. Distance Error Measurements from Trimble Data

No.	Measured Error	Error²
1	1.570935	2.46783677
2	1.062804	1.12955234
3	1.055718	1.1145405
4	1.065533	1.13536057
5	1.055718	1.1145405
6	1.042738	1.08730254
7	1.064417	1.13298355
8	1.048885	1.10015974
9	1.061432	1.12663789
10	1.054394	1.11174671
11	1.105066	1.22117086
12	1.083561	1.17410444
13	1.08989	1.18786021
14	1.086403	1.18027148
15	1.083561	1.17410444
16	1.077579	1.1611765
17	1.086403	1.18027148
18	1.091965	1.19238756
19	1.085212	1.17768508
20	1.083715	1.1744382
	AVG	1.21720657
	RMSE	1.10327085

4.4.2. iPhone – Condition 2

For Site 4 the iPhone by itself produced similar results to most of the other sites, having only a few different positions for all 20 collected data points from each application. The Fulcrum application produced four different locations for all collected points ranging from 0.31 meters to 2.97 meters from the test site, and the ArcCollector application produced only one site for each point. The resultant RMSE for the Fulcrum application is 2.69 meters and 2.79 meters for the ArcCollector application. Results for each application are reported separately in Table 31 (Fulcrum) and Table 32 (ArcCollector).

Table 31 (left). Distance Error Measurements for Fulcrum Application
Table 32 (right). Distance Error Measurements for ArcCollector Application

No.	Measured Error	Error²
1	2.968917	8.81446815
2	2.968917	8.81446815
3	2.968917	8.81446815
4	2.968917	8.81446815
5	2.968917	8.81446815
6	2.968917	8.81446815
7	2.968917	8.81446815
8	2.968917	8.81446815
9	2.968917	8.81446815
10	2.968917	8.81446815
11	2.968917	8.81446815
12	2.968917	8.81446815
13	2.659287	7.07180735
14	2.659287	7.07180735
15	2.659287	7.07180735
16	0.314661	0.09901154
17	0.314661	0.09901154
18	0.314661	0.09901154
19	2.968917	8.81446815
20	2.968917	8.81446815
	AVG	7.24575054
	RMSE	2.69179318

No.	Measured Error	Error²
1	2.791552	7.79276257
2	2.791552	7.79276257
3	2.791552	7.79276257
4	2.791552	7.79276257
5	2.791552	7.79276257
6	2.791552	7.79276257
7	2.791552	7.79276257
8	2.791552	7.79276257
9	2.791552	7.79276257
10	2.791552	7.79276257
11	2.791552	7.79276257
12	2.791552	7.79276257
13	2.791552	7.79276257
14	2.791552	7.79276257
15	2.791552	7.79276257
16	2.791552	7.79276257
17	2.791552	7.79276257
18	2.791552	7.79276257
19	2.791552	7.79276257
20	2.791552	7.79276257
	AVG	7.79276257
	RMSE	2.791552

4.4.3. iPhone with BGAN at 2 meters – Condition 3

Each application for Condition 3 worked differently. Where the Fulcrum application remained around the same distance from the test site with data points ranging from 1.93 meters to 2.63 meters and a resultant RMSE of 2.48 meters. The ArcCollector application returned data points that were more than 10 meters from the test site as can be seen in Figure 11 and Table 34. The ArcCollector data points ranged from 8.94 meters to 14.00 meters with a resultant RMSE of 12.49 meters. Results for each application are reported separately in Table 33 (Fulcrum) and Table 34 (ArcCollector).

Table 33 (left). Distance Error Measurements for Fulcrum Application
Table 34 (right). Distance Error Measurements for ArcCollector Application

No.	Measured Error	Error²
1	2.496249	6.23125907
2	2.496249	6.23125907
3	2.496249	6.23125907
4	2.496249	6.23125907
5	2.496249	6.23125907
6	2.496249	6.23125907
7	2.496249	6.23125907
8	2.496249	6.23125907
9	2.496249	6.23125907
10	2.496249	6.23125907
11	2.496249	6.23125907
12	2.496249	6.23125907
13	2.496249	6.23125907
14	2.496249	6.23125907
15	2.634828	6.94231859
16	2.634828	6.94231859
17	2.634828	6.94231859
18	2.125947	4.51965065
19	1.931243	3.72969953
20	2.538699	6.44499261
	AVG	6.13794628
	RMSE	2.4774879

No.	Measured Error	Error²
1	14.002811	196.078716
2	14.002811	196.078716
3	14.002811	196.078716
4	14.002811	196.078716
5	14.002811	196.078716
6	14.002811	196.078716
7	14.002811	196.078716
8	14.002811	196.078716
9	14.002811	196.078716
10	13.040242	170.047911
11	13.040242	170.047911
12	13.040242	170.047911
13	13.040242	170.047911
14	11.40792	130.140639
15	10.63245	113.048993
16	10.63245	113.048993
17	8.944452	80.0032216
18	8.944452	80.0032216
19	8.944452	80.0032216
20	8.944452	80.0032216
	AVG	156.05758
	RMSE	12.4923008

4.4.4. iPhone with BGAN at 4 meters – Condition 4

When the BGAN was moved to 4 meters from the control point, the positional readings for both applications changed. The ArcCollector readings improved slightly, ranging from 8.43 meters to 12.59 meters and a resultant RMSE of 10.67 meters. But the Fulcrum readings decreased in accuracy, ranging from 6.17 meters to 40.86 meters resulting in a RMSE of 12.40 meters, which can be seen in Figure 11 as the yellow pentagons. Results for each application are reported separately in Table 35 (Fulcrum) and Table 36 (ArcCollector).

Table 35 (left). Distance Error Measurements for Fulcrum Application
Table 36 (right). Distance Error Measurements for ArcCollector Application

No.	Measured Error	Error²
1	6.171749	38.0904857
2	6.171749	38.0904857
3	6.171749	38.0904857
4	6.171749	38.0904857
5	6.171749	38.0904857
6	6.171749	38.0904857
7	6.171749	38.0904857
8	6.171749	38.0904857
9	6.171749	38.0904857
10	6.171749	38.0904857
11	6.171749	38.0904857
12	6.171749	38.0904857
13	6.171749	38.0904857
14	6.171749	38.0904857
15	11.295687	127.592545
16	11.295687	127.592545
17	11.295687	127.592545
18	14.956959	223.710623
19	16.353987	267.452891
20	40.857525	1669.33735
	AVG	153.827265
	RMSE	12.402712

No.	Measured Error	Error²
1	10.436536	108.921284
2	10.36293	107.390318
3	10.36293	107.390318
4	10.36293	107.390318
5	10.36293	107.390318
6	10.36293	107.390318
7	12.441479	154.7904
8	12.441479	154.7904
9	12.441479	154.7904
10	12.441479	154.7904
11	12.441479	154.7904
12	12.590743	158.526809
13	10.961557	120.155732
14	10.961557	120.155732
15	8.430342	71.0706662
16	8.430342	71.0706662
17	8.430342	71.0706662
18	8.430342	71.0706662
19	8.852627	78.3690048
20	9.837014	96.7668444
	AVG	113.904083
	RMSE	10.6725856

4.4.5. iPhone with BGAN at 8 meters – Condition 5

Moving the BGAN terminal to 8 meters from the control point caused more changes in the positional readings from both applications, again with different results. Where at 2 meters the Fulcrum application preformed much better, this time it was the ArcCollector application that out-performed. Figure 12 shows how different the findings were for each application at this condition. The orange pentagons at the far reaches of the map represent the Fulcrum readings from this condition and they are hundreds of meters from the test site. The ArcCollector application data points can be seen in Figure 11 and are only exceeded in accuracy by the ArcCollector data points from Condition 2. For this condition, the ArcCollector application data ranged from 1.33 meters to 34.60 meters with a resultant RMSE of 8.13 meters, and the Fulcrum data points ranged from 262.22 meters to 806.20 meters with a resultant RMSE of 730.56 meters, the worst results from any condition at any site. Possible reasons for this large distance are discussed in Chapter 5. Results for each application are reported separately in Table 37 (Fulcrum) and Table 38 (ArcCollector).

Table 37 (left). Distance Error Measurements for Fulcrum Application
Table 38 (right). Distance Error Measurements for ArcCollector Application

No.	Measured Error	Error²
1	262.222854	68760.8252
2	262.222854	68760.8252
3	262.222854	68760.8252
4	262.222854	68760.8252
5	806.19586	649951.765
6	806.19586	649951.765
7	806.19586	649951.765
8	806.19586	649951.765
9	806.19586	649951.765
10	806.19586	649951.765
11	806.19586	649951.765
12	806.19586	649951.765
13	806.19586	649951.765
14	806.19586	649951.765
15	806.19586	649951.765
16	806.19586	649951.765
17	806.19586	649951.765
18	806.19586	649951.765
19	806.19586	649951.765
20	806.19586	649951.765
	AVG	533713.577
	RMSE	730.557032

No.	Measured Error	Error²
1	34.59844	1197.05205
2	1.807212	3.26601521
3	1.807212	3.26601521
4	1.807212	3.26601521
5	1.807212	3.26601521
6	1.807212	3.26601521
7	2.315583	5.36192463
8	2.315583	5.36192463
9	2.315583	5.36192463
10	2.315583	5.36192463
11	2.315583	5.36192463
12	1.325842	1.75785701
13	1.325842	1.75785701
14	1.456526	2.12146799
15	1.456526	2.12146799
16	3.811221	14.5254055
17	3.811221	14.5254055
18	3.811221	14.5254055
19	3.811221	14.5254055
20	3.811221	14.5254055
	AVG	66.0288714
	RMSE	8.12581512

4.5. Site 5 C099

Site 5 was located in a residential area with tree canopy directly over the testing site. The tree canopy did not completely cover the site but was the best example of tree cover over a NGS benchmark that was found for use in this study. The roadway runs east to west, and the north side of the site is covered by trees that extend overhead. The BGAN terminal was moved to the south for the distance conditions. Collection occurred on June 23, 2018 starting at seven pm. Figure 13 shows the site photos from this site with a picture of the benchmark and pictures from the four cardinal directions.

Figure 13. Photos of each cardinal direction at Site 5 and the benchmark.

As you can see from the photos, the benchmark was on the side of the road close to the vegetation and further away from the buildings, however the coordinates provided by the NGS interactive map appear at a different location. The site map (Figure 14) of all collected points for each condition shows where the NGS coordinates would place the benchmark, represented by the green star, while the green square represents the approximate placement of the actual benchmark and where the data was collected.

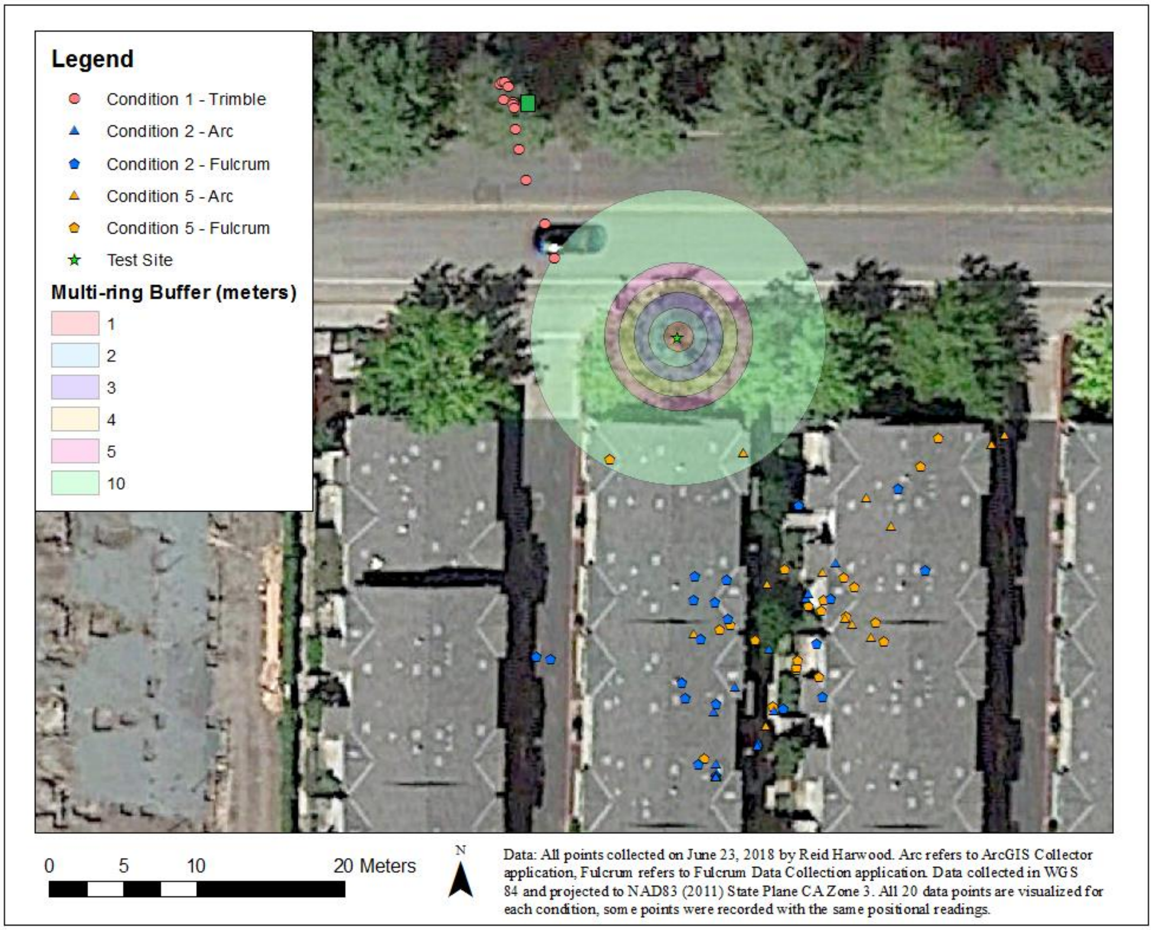


Figure 14. Site 5: Data points for all conditions.

Because of where the found benchmark was located, the experiment had to be abbreviated for safety reasons to both the collector and the BGAN terminal. Placing the terminal 2, 4 or even 8 meters from the test site would have put the terminal in the roadway, which was deemed an unnecessary risk. Because of that, only two conditions were tested with the iPhone; Condition 2 and Condition 5 but the distance for Condition 5 was set at 10 meters rather than 8 meters so that the terminal was out of the roadway. All measurements were performed using the NGS coordinates, because exact coordinates could not be easily determined. This is why the buffer rings remain around the green star rather than the green square, to show where the measurements were made from.

4.5.1. Trimble Geo XH 6000 – Condition 1

Even by using the stated NGS benchmark, the Trimble data resulted in a lower RMSE than the other conditions. Because the location of the test site marked by the green square in Figure 14 is not confirmed, the NGS benchmark coordinates were used as the control point location. The collected data ranged from 13.86 meters to 18.71 meters and a resultant RMSE of 17.27 meters for the Trimble unit. Table 39 shows the distances of each data point from the stated control point and the calculated RMSE.

Table 39. Distance Error Measurements from Trimble Data

No.	Measured Error	Error²
1	15.96739	254.957543
2	15.39396	236.974004
3	14.549917	211.700085
4	13.862748	192.175782
5	16.496521	272.135205
6	17.327048	300.226592
7	17.368597	301.668162
8	17.368597	301.668162
9	17.445869	304.358345
10	17.553058	308.109845
11	17.646586	311.401997
12	17.731731	314.414284
13	17.841566	318.321477
14	17.949032	322.16775
15	18.088199	327.182943
16	18.248003	332.989613
17	18.36205	337.16488
18	18.345073	336.541703
19	18.266568	333.667506
20	18.714518	350.233184
	AVG	298.402953
	RMSE	17.2743438

4.5.2. iPhone – Condition 2

As Figure 14 shows, both applications performed more poorly than the Trimble device. The Fulcrum application data ranged from 14.08 meters to 29.77 meters with a RMSE of 22.28 meters for Condition 2. The ArcCollector data ranged from 18.70 meters to 89.85 meters with a resultant RMSE of 33.01 meters. As the site photos in Figure 13 show both buildings and tree canopy surrounded the site, so it is not surprising that both applications performed so poorly. What is interesting is that both applications had fewer duplications in positional recordings than at other sites. This may have been because the iPhone was constantly trying to improve its accuracy in such poor conditions. Results for each application are reported separately in Table 40 (Fulcrum) and Table 41 (ArcCollector).

Table 40 (left). Distance Error Measurements for Fulcrum Application
Table 41 (right). Distance Error Measurements for ArcCollector Application

No.	Measured Error	Error²
1	19.347825	374.338332
2	29.772907	886.425991
3	28.905596	835.53348
4	23.585341	556.26831
5	23.34352	544.919926
6	24.393281	595.032158
7	26.155938	684.133093
8	23.352774	545.352053
9	26.230939	688.062161
10	22.764653	518.229426
11	20.522105	421.156794
12	24.9275	621.380256
13	18.095461	327.445709
14	14.084204	198.364802
15	16.737947	280.15887
16	18.108511	327.918171
17	16.222694	263.175801
18	20.480375	419.44576
19	23.000789	529.036295
20	17.770916	315.805455
	AVG	496.609142
	RMSE	22.2847289

No.	Measured Error	Error²
1	26.129682	682.760281
2	18.701107	349.731403
3	21.996224	483.83387
4	24.022382	577.074837
5	25.451527	647.780227
6	29.011409	841.661852
7	29.54374	872.832573
8	29.785277	887.162726
9	29.850334	891.04244
10	29.848632	890.940832
11	29.848632	890.940832
12	89.848632	8072.77667
13	29.848632	890.940832
14	29.848632	890.940832
15	19.720817	388.910623
16	19.530176	381.427775
17	27.924374	779.770663
18	28.09058	789.080685
19	28.187461	794.532958
20	28.187461	794.532958
	AVG	1089.93379
	RMSE	33.0141454

4.5.3. iPhone with BGAN at 10 meters – Condition 5

As mentioned earlier, the conditions for this site were abbreviated because of necessity and only one condition using the BGAN terminal was tested. The BGAN terminal was placed at a distance of 10 meters from the testing site so that the terminal was safely out of the road. The terminal was moved to the South, as that is the direction the roadway was, and was located near the sidewalk in front of the building that can be seen in the South photo in Figure 13. Both applications exhibited improvements to their respective positional readings but the ArcCollector application seemed to be more affected by the BGAN terminal, with data ranging from 9.01 meters to 26.98 meters and a resultant RMSE of 22.01 meters which was an 11 meter improvement from the initial condition. The Fulcrum application data ranged from 17.29 meters to 28.56 meters and a resultant RMSE of 22.09 meters, which is still an improvement. Results for each application are reported separately in Table 42 (Fulcrum) and Table 43 (ArcCollector).

Table 42 (left). Distance Error Measurements for Fulcrum Application
Table 43 (right). Distance Error Measurements for ArcCollector Application

No.	Measured Error	Error²
1	24.848341	617.44005
2	23.530026	553.662124
3	18.941939	358.797053
4	18.667723	348.483882
5	23.852984	568.964846
6	23.73075	563.148496
7	23.303115	543.035169
8	20.2536698	410.21114
9	20.3433943	413.853692
10	20.714509	429.090883
11	19.7486553	390.009386
12	24.904992	620.258627
13	25.768109	663.995441
14	22.102399	488.516042
15	17.28659	298.826194
16	28.562307	815.805381
17	20.897822	436.718964
18	19.997171	399.886848
19	19.763382	390.591268
20	21.176314	448.436275
	AVG	487.986588
	RMSE	22.0904185

No.	Measured Error	Error²
1	20.122157	404.901202
2	16.819661	282.900996
3	18.687418	349.219592
4	26.975737	727.690387
5	26.962326	726.967023
6	26.962326	726.967023
7	26.962029	726.951008
8	26.962326	726.967023
9	24.220812	586.647734
10	22.797005	519.703437
11	22.199998	492.839911
12	9.005231	81.0941854
13	9.005231	81.0941854
14	23.174007	537.0346
15	22.561792	509.034458
16	22.482813	505.47688
17	22.482813	505.47688
18	22.482813	505.47688
19	19.329601	373.633475
20	17.781698	316.188784
	AVG	484.313283
	RMSE	22.0071189

4.6. Site 6 Circle of Palms

The final two sites used city landmarks as control points and were determined using the methods described in section 3.2.3. Both locations were located in downtown San Jose fairly close to each other. The first one was at a landmark called the Circle of Palms and is located in the middle of several buildings of at least three stories. As can be seen in Figure 15, which shows the site photos and the designated control point, the site was several meters from the side of all the buildings and in theory provided less interference than Site 7, which was only 1 meter away from the side of a building. The blue X marks the exact location the tripod was setup over for data collection as it was at the center of the landmark.

Figure 15. Photos of each cardinal direction at Site 6 and the control point.

For this site, the BGAN terminal was moved to the west for the distance conditions, as that direction was the least covered by buildings and was thought to provide the best chance of improving the BGAN's signal. Collection occurred on June 28, 2018 starting at six pm. Figure 16 shows the site map of all collected points for this site.

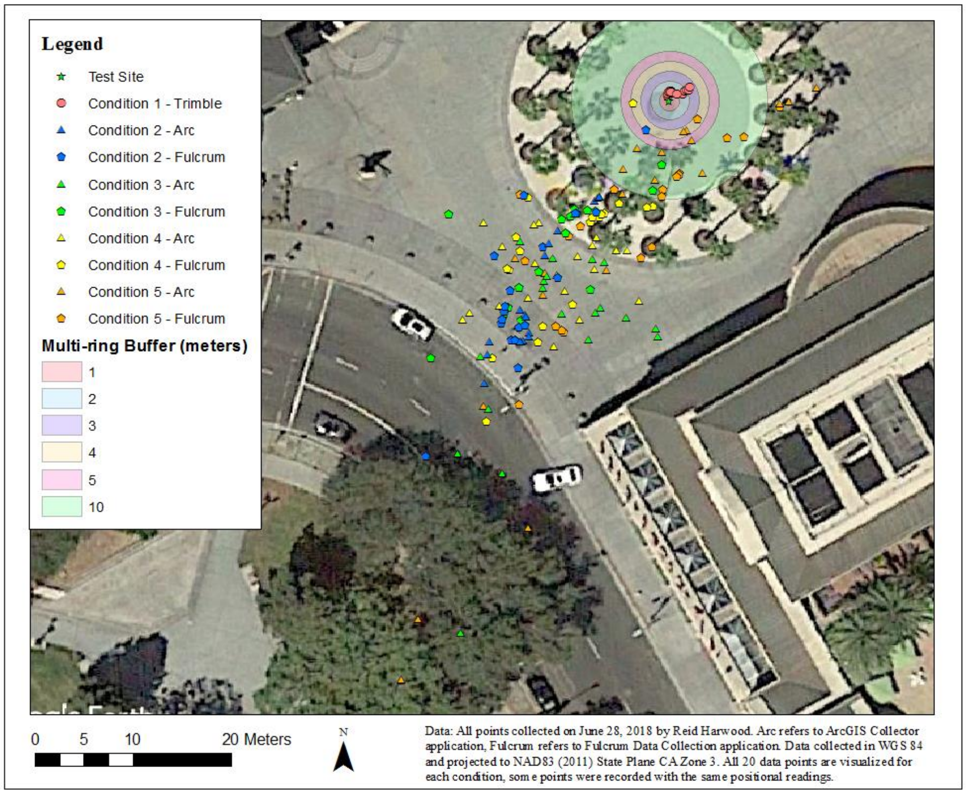


Figure 16. Site 6: Data points for all conditions.

4.6.1. Trimble Geo XH 6000 – Condition 1

The Trimble unit was able to collect all points within 3 meters of the test site and were clustered together. The majority of the collected points were less than a meter away from the test site, producing the most accurate results for any site tested. The data ranged from 0.52 meters to 2.46 meters and the calculated RMSE for this condition was 1.28 meters. Table 44 shows the distance of each data point from the actual control point and the calculated RMSE.

Table 44. Distance Error Measurements from Trimble Data

No.	Measured Error	Error²
1	1.585372	2.51340438
2	1.864692	3.47707625
3	2.0520953	4.21109512
4	2.290186	5.24495191
5	2.461431	6.05864257
6	0.518974	0.26933401
7	0.664154	0.44110054
8	0.835151	0.69747719
9	0.850564	0.72345912
10	0.958181	0.91811083
11	0.991167	0.98241202
12	1.013984	1.02816355
13	0.938618	0.88100375
14	0.886473	0.78583438
15	0.863326	0.74533178
16	0.841946	0.70887307
17	0.831718	0.69175483
18	0.845439	0.7147671
19	1.038343	1.07815619
20	0.831718	0.69175483
	AVG	1.64313517
	RMSE	1.28184834

4.6.2. iPhone – Condition 2

The collected points for both applications were very similar for this condition. Both applications recorded separate positions for each collected data point, with the exception of only two data points in the ArcCollector application. The Fulcrum data ranged from 3.78 meters to 43.83 meters and a resultant RMSE of 24.86 meters. The ArcCollector data ranged from 12.11 meters to 34.40 meters with a resultant RMSE of 23.70 meters. Results for each application are reported separately in Table 45 (Fulcrum) and Table 46 (ArcCollector).

Table 45 (left). Distance Error Measurements for Fulcrum Application
Table 46 (right). Distance Error Measurements for ArcCollector Application

No.	Measured Error	Error²
1	23.738818	563.53148
2	29.231135	854.459253
3	29.000782	841.045357
4	27.638585	763.891381
5	43.825197	1920.64789
6	13.585641	184.569641
7	17.61601	310.323808
8	28.371851	804.961929
9	28.043239	786.423254
10	27.237157	741.862721
11	25.272099	638.678988
12	21.296726	453.550538
13	27.148831	737.059025
14	31.236643	975.727866
15	26.819821	719.302798
16	19.684426	387.476627
17	14.821227	219.66877
18	3.780849	14.2948192
19	14.907068	222.220676
20	14.821227	219.66877
	AVG	617.96828
	RMSE	24.8589678

No.	Measured Error	Error²
1	34.396277	1183.10387
2	31.864152	1015.32418
3	30.690905	941.93165
4	26.206264	686.768273
5	26.342187	693.910816
6	26.384358	696.134347
7	27.660662	765.112222
8	28.005433	784.304278
9	28.639885	820.243013
10	28.813712	830.229999
11	28.895366	834.942176
12	20.2397	409.645456
13	19.041573	362.581502
14	17.455406	304.691199
15	12.761712	162.861293
16	12.320562	151.796248
17	12.174038	148.207201
18	12.111166	146.680342
19	12.111166	146.680342
20	12.174038	148.207201
	AVG	561.667781
	RMSE	23.6995312

It is interesting to see that the ArcCollector application improved on the collected positions, compared to the Fulcrum application that was much less precise in the positions it recorded. Ultimately, both applications performed similarly in this condition.

4.6.3. iPhone with BGAN at 2 meters – Condition 3

The results from this condition were similar to the results from Site 4 for Condition 5 in that each application had a different reaction to the introduction of the BGAN terminal. At Site 4 and Condition 5, the Fulcrum application decreased in accuracy significantly while the ArcCollector application improved its accuracy. Similar results were obtained with this condition, but this time it was the Fulcrum application that performed better and the ArcCollector application that degraded. Figure 16 does not illustrate this well because the majority of points are clustered together to the southwest of the test site. The Fulcrum data ranged from 6.55 meters to 35.74 meters with a resultant RMSE of 20.83 meters, while the ArcCollector data ranged from 14.99 meters to 41.89 meters with a resultant RMSE of 28.60 meters. The ArcCollector data was not as far off as the Fulcrum data from Site 4 Condition 5 (750 meters) but it is peculiar that each application had a different reaction to the introduction of the BGAN terminal. Results for each application are reported separately in Table 47 (Fulcrum) and Table 48 (ArcCollector).

Table 47 (left). Distance Error Measurements for Fulcrum Application
Table 48 (right). Distance Error Measurements for ArcCollector Application

No.	Measured Error	Error²
1	16.253266	264.168656
2	6.545656	42.8456125
3	6.545656	42.8456125
4	26.937308	725.618562
5	9.267894	85.8938592
6	15.467563	239.245505
7	26.2633279	689.762392
8	20.835353	434.111935
9	21.926799	480.784514
10	24.448663	597.737122
11	24.448663	597.737122
12	35.743216	1277.57749
13	25.262082	638.172787
14	25.262082	638.172787
15	13.543583	183.42864
16	13.925194	193.911028
17	14.61297	213.538892
18	17.107677	292.672612
19	27.3742	749.346826
20	17.107677	292.672612
	AVG	434.012228
	RMSE	20.8329601

No.	Measured Error	Error²
1	20.93613	438.321539
2	17.987743	323.558898
3	17.750894	315.094238
4	24.302054	590.589829
5	36.433415	1327.39373
6	41.888173	1754.61904
7	41.569667	1728.03721
8	22.223447	493.881597
9	24.134173	582.458306
10	23.313989	543.542083
11	58.2569	3393.8664
12	32.34845	1046.42222
13	14.993345	224.800394
14	19.943056	397.725483
15	22.446685	503.853667
16	21.762185	473.592696
17	22.99451	528.74749
18	22.527649	507.494969
19	22.873645	523.203636
20	25.71857	661.444843
	AVG	817.932413
	RMSE	28.5995177

4.6.4. iPhone with BGAN at 4 meters – Condition 4

For this condition, each application returned results that were similar to other sites. As stated earlier, the BGAN terminal was moved to the West for the distance testing conditions, toward a space between the buildings. The Fulcrum application remained similar to the previous condition, with data ranging from 3.71 meters to 37.55 meters and a resultant RMSE of 20.40 meters improving by less than half a meter. The ArcCollector application data improved as well, ranging from 15.79 meters to 30.72 meters and a resultant RMSE of 22.44 meters. The site map does not show this because the points are still clustered to the southwest of the test site but has fewer outliers, which improved the calculated RMSE. Results for each application are reported separately in Table 49 (Fulcrum) and Table 50 (ArcCollector).

Table 49 (left). Distance Error Measurements for Fulcrum Application
Table 50 (right). Distance Error Measurements for ArcCollector Application

No.	Measured Error	Error²
1	17.446529	304.381374
2	14.761511	217.902207
3	14.761511	217.902207
4	13.804692	190.569521
5	11.583695	134.18199
6	23.700702	561.723275
7	23.770677	565.045085
8	21.525674	463.354641
9	10.897952	118.765358
10	11.096107	123.123591
11	13.24984	175.55826
12	13.508309	182.474412
13	14.126211	199.549837
14	20.866304	435.402643
15	3.709819	13.762757
16	31.742138	1007.56332
17	37.551178	1410.09097
18	26.31791	692.632387
19	28.015364	784.86062
20	22.939057	526.200336
	AVG	416.25224
	RMSE	20.4022607

No.	Measured Error	Error²
1	24.759955	613.055372
2	18.399608	338.545575
3	22.67366	514.094858
4	16.696948	278.788073
5	15.793478	249.433947
6	18.18221	330.59276
7	18.759492	351.91854
8	21.510104	462.684574
9	22.573728	509.573196
10	16.168815	261.430579
11	15.847001	251.127441
12	22.115634	489.101267
13	18.755052	351.751976
14	24.127507	582.136594
15	30.721972	943.839564
16	29.683674	881.120502
17	26.995546	728.759504
18	27.152267	737.245603
19	27.644738	764.231539
20	20.696665	428.351942
	AVG	503.38917
	RMSE	22.4363359

4.6.5. iPhone with BGAN at 8 meters – Condition 5

Both applications preformed differently for this condition as well. As with other conditions at this site, the Fulcrum application produced more accurate results than the

ArcCollector application but also improved on the previous accuracy readings. The Fulcrum data ranged from 3.43 meters to 34.52 meters with a resultant RMSE of 16.95 meters, the best results from the site. The ArcCollector application data ranged from 3.48 meters to 58.70 meters and a resultant RMSE of 24.75 meters, which is a decrease in accuracy from the previous condition but an improvement from Condition 2 where the BGAN terminal was not utilized. Results for each application are reported separately in Table 51 (Fulcrum) and Table 52 (ArcCollector).

Table 51 (left). Distance Error Measurements for Fulcrum Application
Table 52 (right). Distance Error Measurements for ArcCollector Application

No.	Measured Error	Error²
1	8.477464	71.8673959
2	7.028838	49.4045636
3	17.178967	295.116907
4	15.611785	243.727831
5	11.330766	128.386258
6	34.520032	1191.63261
7	10.618249	112.747212
8	3.438833	11.8255724
9	21.940828	481.399933
10	7.569196	57.2927281
11	7.519774	56.547001
12	7.704189	59.3545281
13	8.991332	80.8440511
14	9.774201	95.5350052
15	14.963609	223.909594
16	16.19744	262.357063
17	25.859664	668.722222
18	25.831957	667.290002
19	25.757448	663.446127
20	17.952601	322.295883
	AVG	287.185124
	RMSE	16.9465372

No.	Measured Error	Error²
1	18.401946	338.631617
2	5.330775	28.4171621
3	4.615316	21.3011418
4	8.220383	67.5746967
5	5.880719	34.582856
6	8.42571	70.992589
7	10.670744	113.864778
8	22.434221	503.294272
9	12.13963	147.370617
10	11.236996	126.270079
11	15.08272	227.488443
12	8.176363	66.8529119
13	23.610005	557.432336
14	58.701282	3445.84051
15	65.05008	4231.51291
16	36.442717	1328.07162
17	21.739697	472.614426
18	21.150617	447.348599
19	3.5507	12.6074705
20	3.48368	12.1360263
	AVG	612.710253
	RMSE	24.7529847

It is possible that the BGAN was able to acquire a better signal as it was moved further away from the test site. This is because the terminal was moved to the West of the test site where an opening in the buildings was located, possibly reducing the effects of building shadows. It is not definitive that this is what caused the improvements seen in either application, but it is a possibility. In order to state this with any certainty, more tests would need to be conducted.

4.7. Site 7 San Jose Museum of Art

This final site was in the shadow of buildings, as was Site 6. However, the control point was much closer to the side of a building at this site. This site was chosen to be as close to the CA Historic Site plaque at the far west end of the San Jose Museum of Art, about 1 meter from the side of the building. The BGAN terminal was moved to the south for the distance conditions, away from the building. Collection occurred on June 28, 2018 starting at six am. Figure 17 shows the site photos from Site 7 with pictures in each cardinal direction and the designated control point. The blue X mark shows the exact control point used for data collection.

Figure 17. Photos of each cardinal direction at Site 7 and the control point.

As the results in Figure 18 show, being close to the side of the building had a dramatic effect on the accuracy of both applications at this site.

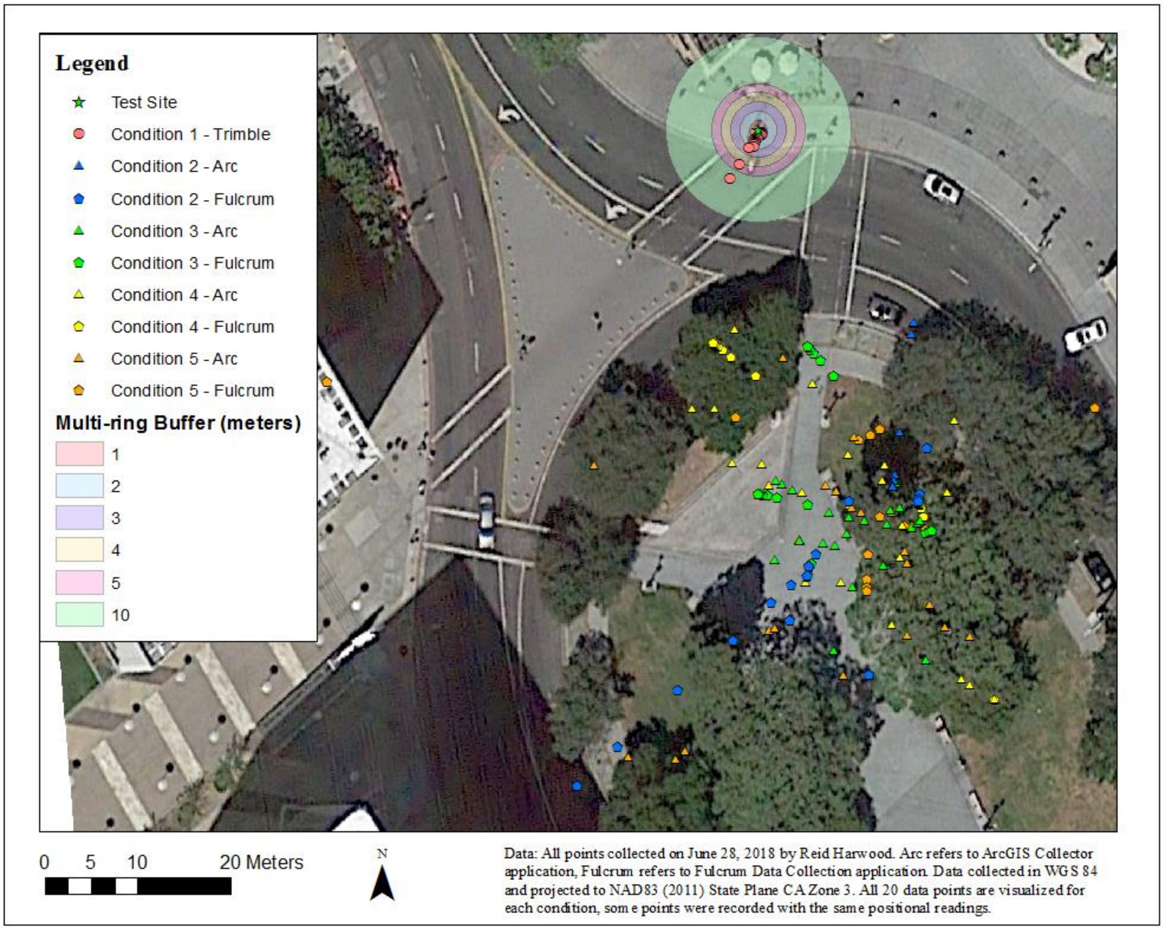


Figure 18. Site 7: Data points for all conditions.

4.7.1. Trimble Geo XH 6000 – Condition 1

This location was thought to be the one that would cause problems for the Trimble unit being that these units are known to have difficulties recording points in building shadows. It was thought that the results from this condition would be significantly poorer in accuracy than the other sites but that was not the case. The Trimble data ranged from 0.54 meters to 5.99 meters and returned a RMSE of 1.99 meters, which is similar to the other testing sites. Table 53 shows the distance of each data point from the actual control point and the calculated RMSE, with only three points being recorded at a distance of more than 2 meters from the testing site. The iPhone did not perform as well, as can be seen in Figure 18.

Table 53. Distance Error Measurements from Trimble Data

No.	Measured Error	Error²
1	4.157371	17.2837336
2	5.999865	35.99838
3	0.552265	0.30499663
4	0.637914	0.40693427
5	0.604497	0.36541662
6	0.549762	0.30223826
7	0.544149	0.29609813
8	0.646449	0.41789631
9	0.768018	0.58985165
10	0.885665	0.78440249
11	1.024284	1.04915771
12	1.11587	1.24516586
13	1.154941	1.33388871
14	1.214136	1.47412623
15	1.335997	1.78488798
16	1.427588	2.0380075
17	1.584703	2.5112836
18	1.650533	2.72425918
19	1.863978	3.47441398
20	2.18171	4.75985852
	AVG	3.95724986
	RMSE	1.98928376

4.7.2. iPhone – Condition 2

Both applications returned results that were very far removed from the testing location. The Fulcrum data ranged from 41.25 meters to 73.34 meters and had a resultant RMSE of 52.91 meters and the ArcCollector data ranged from 26.73 meters to 41.18 meters and resultant RMSE of 39.01 meters. Figure 16 does show this with the blue pentagons trailing off to the far South and West of the image while the blue triangles are still to the South of the test site but at a much closer distance. Results for each application are reported separately in Table 54 (Fulcrum) and Table 55 (ArcCollector).

Table 54 (left). Distance Error Measurements for Fulcrum Application
Table 55 (right). Distance Error Measurements for ArcCollector Application

No.	Measured Error	Error²
1	43.644166	1904.81323
2	41.257306	1702.1653
3	46.232075	2137.40476
4	47.440603	2250.61081
5	47.440603	2250.61081
6	47.359777	2242.94848
7	60.98956	3719.72643
8	68.218081	4653.70658
9	73.33739	5378.37277
10	73.33739	5378.37277
11	55.046308	3030.09602
12	51.043592	2605.44828
13	49.172895	2417.9736
14	59.972546	3596.70627
15	52.966843	2805.48646
16	48.508253	2353.05061
17	48.278216	2330.78614
18	38.696808	1497.44295
19	42.993662	1848.45497
20	43.422376	1885.50274
	AVG	2799.484
	RMSE	52.9101502

No.	Measured Error	Error²
1	27.64831	764.429046
2	26.83123	719.914903
3	26.729236	714.452057
4	36.054865	1299.95329
5	40.005972	1600.4778
6	40.622886	1650.21887
7	40.622886	1650.21887
8	41.057185	1685.69244
9	41.155567	1693.7807
10	41.183502	1696.08084
11	41.183502	1696.08084
12	41.155567	1693.7807
13	41.183876	1696.11164
14	41.183902	1696.11378
15	41.183876	1696.11164
16	41.170585	1695.01707
17	41.183876	1696.11164
18	41.057185	1685.69244
19	41.183876	1696.11164
20	41.170585	1695.01707
	AVG	1521.06836
	RMSE	39.0008764

4.7.3. iPhone with BGAN at 2 meters – Condition 3

Adding the BGAN connection to the iPhone again improved the accuracy of the data collected by the Fulcrum application but not the ArcCollector application. The Fulcrum data ranged from 23.93 meters to 47.13 meters with a resultant RMSE of 38.64, while the ArcCollector data ranged from 37.86 meters to 60.07 meters with a resultant RMSE of 45.74 meters. It is very odd that the accuracy of data collected through one application would improve by more than 13 meters while the other degraded by almost 6 meters. One would presume that if the positional accuracy of one application improved then the other would also. Results for each application are reported separately in Table 56 (Fulcrum) and Table 57 (ArcCollector).

Table 56 (left). Distance Error Measurements for Fulcrum Application
Table 57 (right). Distance Error Measurements for ArcCollector Application

No.	Measured Error	Error²
1	47.138549	2222.0428
2	47.062387	2214.86827
3	47.143804	2222.53826
4	47.117003	2220.01197
5	40.74676	1660.29845
6	39.700425	1576.12375
7	39.444191	1555.8442
8	39.325524	1546.49684
9	39.268641	1542.02617
10	39.240803	1539.84062
11	39.213771	1537.71984
12	39.213771	1537.71984
13	39.268641	1542.02617
14	39.268641	1542.02617
15	39.213771	1537.71984
16	37.704504	1421.62962
17	25.766807	663.928343
18	24.814716	615.77013
19	24.342306	592.547861
20	23.931054	572.695346
	AVG	1493.19372
	RMSE	38.6418649

No.	Measured Error	Error²
1	48.909415	2392.13088
2	60.071639	3608.60181
3	56.824699	3229.04642
4	50.38143	2538.28849
5	46.040452	2119.72322
6	45.771286	2095.01062
7	45.676111	2086.30712
8	43.626292	1903.25335
9	45.604133	2079.73695
10	40.936064	1675.76134
11	43.499212	1892.18144
12	44.815393	2008.41945
13	42.914532	1841.65706
14	42.037935	1767.18798
15	39.087678	1527.84657
16	38.255469	1463.48091
17	37.864378	1433.71112
18	46.39293	2152.30395
19	45.083126	2032.48825
20	44.654494	1994.02383
	AVG	2092.05804
	RMSE	45.739021

4.7.4. iPhone with BGAN at 4 meters – Condition 4

As stated earlier, the BGAN terminal was moved to the South, away from the building. The results from this condition do not shed much light on what caused the differences in RMSE from the last condition. Both applications seemed to remain consistent between these two conditions, with the Fulcrum data ranging from 23.47 meters to 66.47 meters with a resultant RMSE of 38.97 meters. The ArcCollector data ranged from 21.64 meters to 64.05 meters and a resultant RMSE of 43.40 meters. Results for each application are reported separately in Table 58 (Fulcrum) and Table 59 (ArcCollector).

Table 58 (left). Distance Error Measurements for Fulcrum Application
Table 59 (right). Distance Error Measurements for ArcCollector Application

No.	Measured Error	Error²
1	66.470424	4418.31727
2	45.320678	2053.96385
3	44.435115	1974.47945
4	43.739491	1913.14307
5	43.739491	1913.14307
6	43.775858	1916.32574
7	43.715649	1911.05797
8	43.715649	1911.05797
9	43.715649	1911.05797
10	44.036295	1939.19528
11	43.775858	1916.32574
12	43.906884	1927.81446
13	26.551801	704.998136
14	24.648724	607.559595
15	24.028417	577.364824
16	23.736321	563.412935
17	23.594986	556.723364
18	23.52557	553.452444
19	23.473973	551.027408
20	23.473973	551.027408
	AVG	1518.5724
	RMSE	38.9688645

No.	Measured Error	Error²
1	28.089526	789.021471
2	30.439081	926.537652
3	30.916191	955.810866
4	36.078896	1301.68674
5	38.356126	1471.1924
6	36.107928	1303.78246
7	21.635201	468.081922
8	48.633686	2365.23541
9	49.012772	2402.25182
10	55.369091	3065.73624
11	64.048206	4102.17269
12	63.162934	3989.55623
13	40.113988	1609.13203
14	49.659584	2466.07428
15	44.163416	1950.40731
16	39.437251	1555.29677
17	36.383085	1323.72887
18	38.634551	1492.62853
19	45.430824	2063.95977
20	45.430824	2063.95977
	AVG	1883.31266
	RMSE	43.3971504

4.7.5. iPhone with BGAN at 8 meters – Condition 5

For this condition, data collected through both applications degraded in accuracy from the previous condition. The Fulcrum data ranged from 23.46 meters to 53.81 meters and a resultant RMSE of 41.61 meters, a decrease of less than 2 meters. The ArcCollector data ranged from 24.74 meters to 69.06 meters and a resultant RMSE of 48.99 meters, a decrease of more than 5 meters. Results for each application are reported separately in Table 60 (Fulcrum) and Table 61 (ArcCollector).

Table 60 (left). Distance Error Measurements for Fulcrum Application
Table 61 (right). Distance Error Measurements for ArcCollector Application

No.	Measured Error	Error²
1	23.459028	550.325995
2	35.078899	1230.52916
3	35.053559	1228.752
4	35.053559	1228.752
5	47.25559	2233.09079
6	49.787536	2478.79874
7	50.645509	2564.96758
8	51.069991	2608.14398
9	34.764245	1208.55273
10	34.864186	1215.51147
11	34.764245	1208.55273
12	34.764245	1208.55273
13	34.764245	1208.55273
14	31.012819	961.794942
15	53.806751	2895.16645
16	47.066111	2215.2188
17	43.694271	1909.18932
18	45.595139	2078.9167
19	46.803813	2190.59691
20	46.99279	2208.32231
	AVG	1731.6144
	RMSE	41.6126712

No.	Measured Error	Error²
1	40.325378	1626.13611
2	40.149906	1612.01495
3	48.142055	2317.65746
4	49.464447	2446.73152
5	39.054302	1525.2385
6	34.748244	1207.44046
7	24.741841	612.158696
8	24.741841	612.158696
9	54.455959	2965.45147
10	59.564161	3547.88928
11	42.718763	1824.89271
12	42.718763	1824.89271
13	41.771948	1744.89564
14	42.061479	1769.16802
15	43.775275	1916.2747
16	59.27591	3513.63351
17	69.055451	4768.65531
18	68.482322	4689.82843
19	67.419247	4545.35487
20	54.089295	2925.65183
	AVG	2399.80624
	RMSE	48.9878173

4.8. Summary

Overall, it is clear that the use of the BGAN terminal did have an effect on the positional readings of the iPhone but how much and whether they were improved or not depended on the testing site and the application being used. Table 62 shows a summary of all sites, listing the lowest and the highest RMSE, as well as which application and condition they were from. An in-depth discussion of the findings and implications are covered in Chapter 5.

Table 62: Summary of Low RMSE (most accurate) and High RMSE (least accurate)

Site	Trimble Accuracy (for reference only)	Lowest RMSE	Condition (Application)	Highest RMSE	Condition (Application)
1	1.44	1.78	Condition 4 (ArcCollector)	8.13	Condition 2 (ArcCollector)
2	3.10	3.87	Condition 2 (Fulcrum)	10.37	Condition 5 (Fulcrum)
3	1.97	1.47	Condition 2 (ArcCollector)	6.22	Condition 5 (Fulcrum)
4	1.10	2.48	Condition 3 (Fulcrum)	730.56	Condition 5 (Fulcrum)
5	17.27	22.01	Condition 5 (ArcCollector)	33.01	Condition 2 (ArcCollector)
6	1.28	16.95	Condition 5 (Fulcrum)	28.60	Condition 3 (ArcCollector)
7	1.99	38.64	Condition 3 (Fulcrum)	52.91	Condition 2 (Fulcrum)

Chapter 5 Discussion and Conclusion

This thesis represents the first attempt to use a BGAN terminal in positional data collection. As shown in the results chapter, each application performed differently depending on site and condition. However, it appears that the optimal distance for using the BGAN terminal was between 2 and 4 meters from the testing site. There are several possibilities to why this variation occurred, and these lead to implications for future testing. This chapter discusses the overall findings of the study, the limitations encountered, possible direction of future research, a basic cost benefit analysis, and finally the conclusions reached.

5.1. Overall Findings

With the different results obtained from each site, it is difficult to give a definitive answer as to whether or not the experiment obtained the desired results. As seen in Site 1 (section 4.1), the results obtained using the BGAN terminal were better than the results obtained using only the smartphone for both applications. This improvement from the initial condition (Condition 2) to the testing condition using the BGAN (Condition 3) for both applications shows that it is possible to obtain improved positional readings using this equipment. While the data points were not as accurate as the Trimble results for this site, there was an improvement. However, Site 1 was the control site with the most open space and best line of site to satellites.

While Site 1 showed the most marked and consistent improvement across both applications, other sites did show positive results for at least one application. Sites 6 and 7 showed an improvement for the Fulcrum application when using the BGAN terminal but the ArcCollector application performed worse, increasing the RMSE when using the terminal. Having different results from the two applications seemed to be more common than having consistent results across both applications. This could be due to the processes used by each application to determine a positional fix, which may be different but is unknown because neither company releases information for how they determine positional accuracy. The most information the author could obtain after many attempts at contacting both companies was “they utilize the positional readings of the device” (Esri 2018 and Fulcrum 2015). Further technical details about the inner workings of the device itself were unavailable.

Some of the data that was recorded cannot be explained, as in Site 4 Condition 5 with the Fulcrum application. It is unknown why the results from that test had a RMSE of 730 meters while the ArcCollector application calculated a RMSE of 8 meters. It may have been caused by a problem with the internal capabilities of the phone, or a Wi-Fi connection issue, or possibly a changing positional reading within the BGAN terminal that caused this anomaly. Whatever the cause, it was unique to this site, condition, and application.

The precision of the data was also not consistent across all sites and conditions. The Trimble unit produced more precise data (the data was often clustered together) and more accurate data as expected, but the phone data was either duplicated at single point locations or dispersed over a large area. One possibility of why this occurred is that the phone was trying to improve the positional readings continuously as it was connected to the BGAN terminal. As stated earlier, this is the first attempt to use a BGAN terminal for positional data collection. Being that the Trimble receiver is able to access the GPS satellite network, as well as the GLONASS and Galileo networks it is not surprising that the Trimble receiver had more accurate and precise results. By comparison, the BGAN terminal can only access the GPS satellite system which reduces the number of total satellites that can be accessed resulting in a poorer positional data reading. More information on how the phone and each application determines positional location would be needed to draw a firmer conclusion as to why the points collected using the phone were dispersed in this way.

Overall, it is clear that the BGAN terminal did have an effect on the positional readings of the iPhone but the results were not consistent enough to draw any firm conclusions. It appears the BGAN terminal itself was also affected by each site location and therefore provided different positional readings. It is possible that weaker signals from both the internal Wi-Fi connection and the Inmarsat satellites or possibly poorer GPS fixes occurred, all of which could have had an impact on the recorded positional readings. As distance from a Wi-Fi source increases the connection between devices degrades. Being that the terminal was moved away from the iPhone located at the testing site this degradation of signal must have occurred. In addition, while the BGAN was kept in the same pointing position and angle of declination, changes in the connection between the terminal and the satellites may have occurred but this cannot be confirmed.

5.2. Limitations

The study encountered several obstacles that posed limitations mainly due to time and resources available. The primary obstacle was funding and equipment availability. If more funding was made available, more equipment could have been acquired, such as additional smartphones for testing and a variety of applications (for purchase versus the free applications used) that record positional readings to further understand what was being affected within the smartphone by the BGAN terminal. As described in section 2.4, the BGAN terminal relies on data from the Inmarsat satellites and acquiring this data requires a paid subscription. Because of the funding issues encountered, only a finite amount of data was available which limited the number of collected points and in turn the number of sites used. If funding were not an issue, the concern of data limitations would not be a factor and as many points at as many sites needed could be included.

Another limitation associated with the BGAN terminal was the pre-assembled unit that was used that resulted in a lack of knowledge of the terminal system's set up. Because the terminal was borrowed pre-assembled, there was no way to confirm the current setup of the terminal. Per the terminal manual, the GPS threshold is established and calibrated upon initial use (Cobham 2015). This can be calibrated as precisely as the user wants and because initial setup of the terminal occurred outside of the scope of this study, the author cannot confirm the precision of the GPS threshold. The terminal will work even if the threshold is not met, but with problems as a GPS fix is required to register with the Inmarsat satellites. However, a GPS fix can be determined prior to the terminal being moved after registration and connection has occurred. While a precise GPS fix is not needed for the current uses of a BGAN terminal, it may have a dramatic effect on a study like this one that is concerned with positional readings but further testing with multiple terminals is needed to answer this question.

Using only one model of smartphone was another major restriction of this study. The only smartphone available for testing was an iPhone 6 owned by the author at the time the study was conducted. The instances of the iPhone being "stuck" on a single point (as seen at Site 1, Condition 1 with the ArcCollector application and others) may have been a problem associated with phone used, but cannot be verified because only the one smartphone was used. For future studies, the recommendation would be to source access to a variety of smartphones including ones with an Android operating system, which is discussed in the following section. However, because consistent access to other phones could not be assured, no other smartphone was included. Testing more than one application on the phone was an attempt to counter this limitation.

The last significant limitation to this study was the reliance on others for equipment, mainly the BGAN terminal as discussed above but also the NGS benchmarks used as control points. While it is known that benchmark points are surveyed to be highly accurate and the last update occurred in 2012, it is possible that continuous minor geologic events have shifted these points. While there has not been any major geologic activity in the area since the last update, being that the study area is located in an active geologic area it is possible that this continuous activity caused some shifting in the positions of these benchmarks. This is mentioned because Site 5 is visibly offset from the actual ground location. On the NGS interactive map, the point appears on one side of the street. But when the given coordinates are put into ArcMap, they appear on the other side of the street and a few meters to the east. At a small scale this makes little difference, but for a study like this it makes a considerable amount of difference.

5.3. Future Research

Based on the findings, it is the recommended that future research should be conducted on this same topic by expanding the methodology to cover some of the limitations that were encountered. An expansion of the number and types of smartphones used would be the most effective part of any future research. Using both Apple and Android style phones (Samsung, LG, Google, etc.) would be necessary, but also including different service providers would add another interesting aspect to future research. Research has shown that the cellular signal of a phone influences the positional readings of smartphones (Zandbergden 2009; Hofer & Retscher 2017) and seeing how different service providers affect different types of smartphones would be an interesting expanse of this research.

There are many different types of BGAN terminals and using different types of terminals could be another aspect of future research. While these terminals are not meant for improving positional readings, research into such devices would be beneficial to groups interested in improving positional readings on collection devices. It is plausible that creation of a rudimentary base station type terminal with Wi-Fi capabilities could help to improve positional readings on improvised collection devices from a distance, mainly smartphones. This could be used for data collection by large study groups to collect points in urban planning, archaeology or in other areas that require large groups to collect locational positions.

Incorporating more distance measurements would be another aspect of consideration for future research. Originally, the plan for the study was to collect points for every meter the BGAN terminal was moved away from the control point but this was limited by both time and data usage. Testing the effects of distance at every meter would give a better idea of when the positional accuracy was no longer improving and at what distance the optimal improvement occurred. Along with distance as a factor, connecting multiple devices to the BGAN terminal would be another aspect to consider. Because this study was limited to only one smartphone for collection by a single participant, looking at the possible effects of multiple devices connected to the terminal at one time would be interesting and might tell if positional accuracy degrades with more devices connected.

5.4. Cost Benefit Analysis

A rudimentary cost benefit analysis was conducted to determine if using a BGAN terminal in conjunction with a smartphone is relatable in cost to using a Trimble Geo XH 6000 or a unit of similar accuracy. To start, the cost of a Trimble Geo XH 6000 series receiver is about $4,000 and includes access to the Pathfinder software for downloading and correcting the collected data. However, this cost is for a single unit, and if you have a large group collecting points then multiple units would be required.

The Hughes International 9201 BGAN terminal (the model used in this study) costs just under $5,000 but requires a subscription for data usage much like a cell phone requires a data plan (Ground Control 2018). The cost of a data plan that would allow for unlimited data usage by one or even multiple users would cost about $900 for a year. A similar model of BGAN terminal, the Hughes 9202 model, costs about $3000 and works in the same manner as the 9201 model. With any BGAN terminal paired with a smartphone, applications are needed in order to collect positional readings.

Following what was used in this study, the Fulcrum Data Collection and the ArcGIS Collector applications, prices were considered for both of these applications. For a single user using the basic package, the Fulcrum application costs $20 a month for access to their site for processing and for access to the application for collecting. The ArcCollector application however was paired with an Esri Enterprise account, which is considerably more complex than the simple ArcGIS Online account. The Enterprise account allows access to the entire suite of Esri's tools and services and costs about $30,000. Obviously, this kind of account would need to be purchased by a larger company or organization and most likely would not be purchased and used by a lone enthusiast.

Adding all of these costs together, one gets the approximate number of $3,920 as the minimum cost of conducting research using a BGAN terminal as was done in this study. This estimation only uses the lowest numbers found and uses only the Fulcrum application. To include the Esri Enterprise account would obviously set the cost at a much higher amount, approximately $33,920, which is far beyond what a single Trimble unit costs. If multiple users were looking to conduct research at the same time, then it may be more feasible to utilize a BGAN terminal as was done in this study. Having to purchase 10 or more Trimble units of this caliber would make the cost more than the BGAN terminal and enterprise account, which then may be a consideration.

However, given the results of this experiment and the various conditions tested, the reliability of the BGAN terminal for consistently improving positional accuracy in a smartphone is not where it would need to be for inclusion in a scientific study. Because of this unreliability, the author cannot at this time recommend using this as a substitute for an established form of data collection like the Trimble Geo XH 6000 when precise and accurate data collection for a scientific study is required. However, for an enthusiast who does not want to invest in additional software (Pathfinder) and data processing (post-processing data correction), the BGAN connection may be a viable option. This is especially recommended where regular cell service is limited (Sites 1, 3 and 4) and the BGAN unit can provide not only improved positional accuracy, but also other benefits from Wi-Fi access. Should further research be conducted and a similar device that is capable of reliably improving positional accuracy in a smartphone be created, then there may come a time when the Trimble unit can be replaced for collection with a large survey group.

5.5. Conclusion

The findings from this study show that using a BGAN terminal can provide improved positional accuracy to a smartphone application under the right settings. However, those settings cannot be exactly defined as of yet. Because of the varied nature of the obtained results, the author is unable to definitively state that using a BGAN terminal will improve the positional readings of a smartphone, but the possibility does exist. Further testing is needed to determine what exactly occurs when a smartphone is connected to a BGAN terminal to change the positional readings of the phone. Overall the study shows that it is possible to achieve improved positional accuracy and it is plausible with further investigation that an application could work with the BGAN terminal and help to consistently improve the positional accuracy of a smartphone.

The current uses of a BGAN terminal to provide Internet access to locations that do not allow for phone and Internet services works very well. First responders have success using them after and during disasters. With a little more research and studying, it is plausible that the uses of a BGAN terminal could be expanded to include data collection.

References

"BGAN Supports Emergency Communication in Louisiana." 2007. Satellite Today 6 (171): n/a. http://libproxy.usc.edu/login?url=https://search-proquest-com.libproxy2.usc.edu/docview/207544482?accountid=14749.

Bolstad, Paul. 2012. GIS Fundamentals: A First Text on geographic Information Systems. White Bear Lake: Eider Press.

Breman, Joe. 2002. Marine Geography: GIS for the Oceans and Seas. Redlands: ESRI, Inc.

Buczkowski, Aleks. 2016. "How accurate is your smartphone's GPS in an urban jungle?" Geo Awesomeness. Last modified May 28, 2016. http://geoawesomeness.com/how-accurate-is-your-smartphones-gps-in-an-urban-jungle/.

Cobham. 2015. "Explorer 710 User Manual." Communications and Connectivity. Last modified July 15, 2015. http://www.cobham.com/communications-and-connectivity/satcom/land-mobile-satcom-systems/ultra-portable-bgan/explorer-710/explorer-710-user-manual/docview/.

Esri. 2018. "Collector for ArcGIS." ArcGIS. Accessed June 8, 2018. http://doc.arcgis.com/en/collector/.

Federal Geographic Data Committee (FGDC). 1998. "Part 3: National Standard for Spatial Data Accuracy." In Geospatial Positioning Accuracy Standards, edited by the Subcommittee for Base Cartographic Data, 3-i – 3-25. US Geological Survey.

Fire Rescue 1. 2009. "Inmarsat BGAN to Bring Real-Time GIS Data to Remote Wildfire Teams." Last modified September 21, 2009. https://www.firerescue1.com/fire-products/communications/press-releases/591709-Inmarsat-BGAN-to-Bring-Real-Time-GIS-Data-to-Remote-Wildfire-Teams/.

Fulcrum Mobile Location Leverage (Fulcrum). n.d. "Collect Data Anytime, Anywhere With Fulcrum: Tour." Accessed March 6, 2018. http://www.fulcrumapp.com/tour/.

Gerber, Kathryn E., Christina J. Bohnet, Lauren B. Ebels, and Madison B. Springer. 2016. "Environmental Assessment of a Cirsium Pitcheri Restored Population on the Coast of Lake Michigan." First-Year Research in Earth Sciences, Department of Geology, Geography and Environmental Studies Calvin College 19, no. 19.

Ground Control. 2018. "Products and Services from Ground Control." Accessed July 7, 2018. http://www.groundcontrol.com/Satellite_Internet.htm.

Hasegawa, Hisashi and Tetsuhiko Yoshimura. 2007. "Estimation of GPS Positional Accuracy Under Different Forest Conditions using Signal Interruption Probability." Journal of Forest Research 12 (1): 1-7. doi:10.1007/s10310-006-0245-4. https://search.proquest.com/docview/881642035.

Hester, Thomas R., Harry J .Shafer, and Kenneth L. Feder. 2009. Field Methods in Archaeology / Thomas R. Hester, Harry J. Shafer, Kenneth L. Feder. Walnut Creek: Left Coast Press.

Hofer, Hannes and Guenther Retscher. 2017. "Seamless Navigation using GNSS and Wi-Fi/IN with Intelligent Checkpoints." Journal of Location based Services 11 (3-4): 204-221. doi: 10.1080/17489725.2017.1415385.

Inmarsat. 2013. "About Us." About Us. Accessed April 2, 2018. https://www.inmarsat.com/about-us/.

Lifewire. 2017. "How GPS Works on the iPhone." IPhone & IPod. Last modified June 8, 2017. https://www.lifewire.com/iphone-gps-set-up-1683393

National Geodetic Survey. 2017. "National Geodetic Survey Data Explorer." NGS Interactive Map. Last modified August 8, 2017. https://www.ngs.noaa.gov/NGSDataExplorer/.

Necsoiu, Marius, Marcel Mindrescu, Alexandru Onaca, and Sarah Wigginton. 2016. "Recent Morphodynamics of Alpine Lakes in Southern Carpathian Mountains Using High-Resolution Optical Imagery." Quaternary International 415 (164-174): http://dx.doi.org/10.1016/j.quaint.2015.12.032.

NOAA. 2017. "National Geodetic Survey." NGS Home. Last modified June 12, 2017. https://www.ngs.noaa.gov/.

NOAA. 2017. "National Geodetic Survey." NGS History. Last modified June 5, 2017. https://www.ngs.noaa.gov/web/about_ngs/history/indexhNGS.shtml.

Point of Beginning. 2009. "GIS in the Jungle." Last modified April 1, 2009. http://www.pobonline.com/articles/93095-gis-in-the-jungle.

Trimble. 2013. User Manual: Trimble Geo 7X Handheld. Trimble 1.A: 2013. Westminster, CO: Trimble, approved November 2013.

Trimble. 2012. User Manual: Trimble Juno T41 Handheld. Trimble 1.A: 2012. Westminster, CO: Trimble, approved December 2012.

Trimble. 2018. "GNSS Planning Online." Trimble: GNSS Planning Online. Accessed June 30, 2018. https://www.gnssplanningonline.com/#/settings/.

Usmanov, Bulat, Ionut Cristi Nicu, Iskander Gainullin, and Peter Khomyakov. 2018. "Monitoring and Assessing the Destruction of Archaeological Sites from Kuibyshev Reservoir Coastline, Tatarstan Republic, Russian Federation. A Case Study." Journal of Coastal Conservation 22 (417-429): http://doi.org/10.1007/s11852-017-0590-9.

Walter, Brittany S. and John J. Schultz. 2013. "Mapping Simulated Scenes with Skeletal Remains using Differential GPS in Open Environments: An Assessment of Accuracy and Practicality." Forensic Science International 228 (1-3): e46. doi:10.1016/j.forsciint.2013.02.027.

Wing, Michael G., Aaron Eklund, and Loren D. Kellogg. 2005. "Consumer-Grade Global Positioning System (GPS) Accuracy and Reliability." Journal of Forestry 103 (4): 169. https://search.proquest.com/docview/220823497.

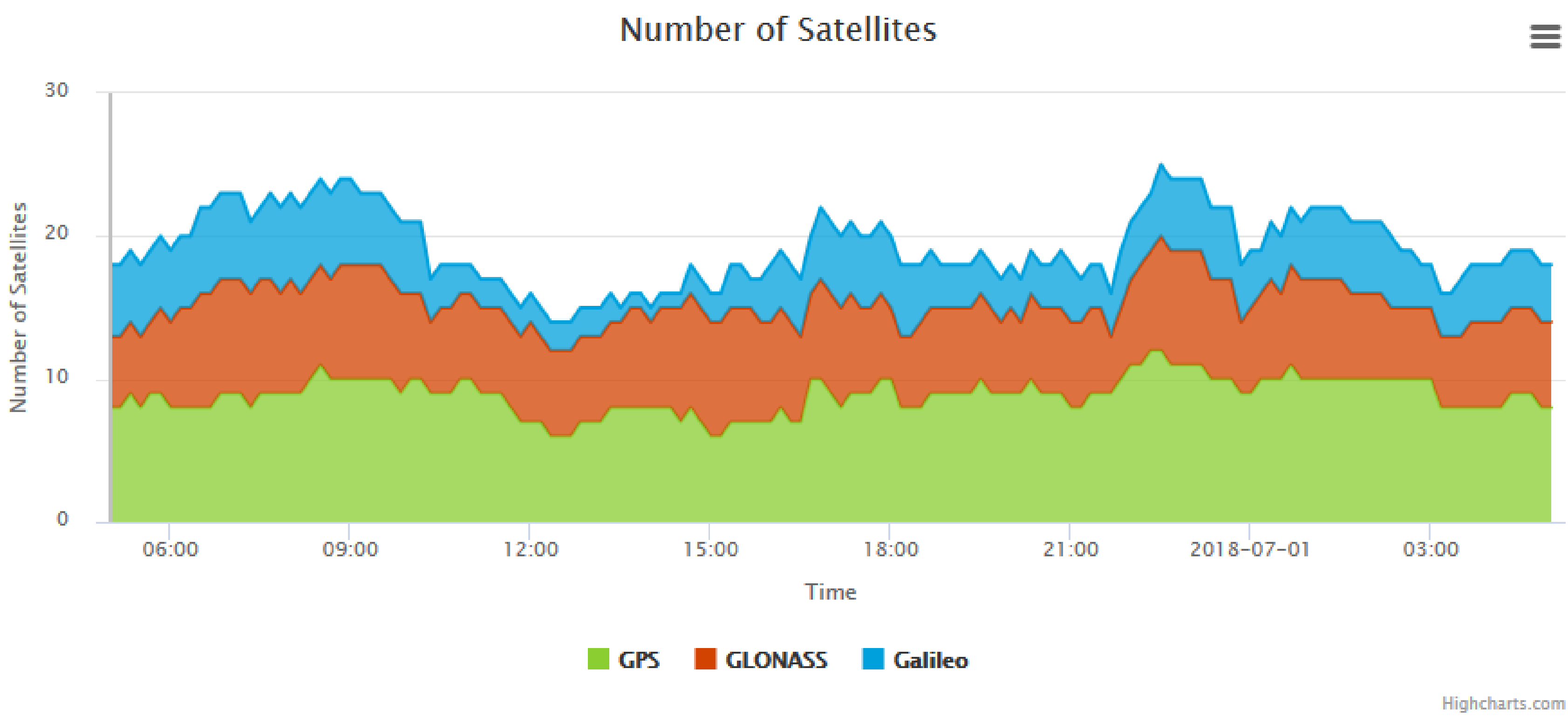
Zandbergen, Paul A. 2009. “Accuracy of iPhone Locations: A Comparison of Assisted GPS, WiFi and Cellular Positioning.” Transactions in GIS 13, no. 1 (Spring): 5-26. doi: 10.1111/j.1467-9671.2009.01152.x.

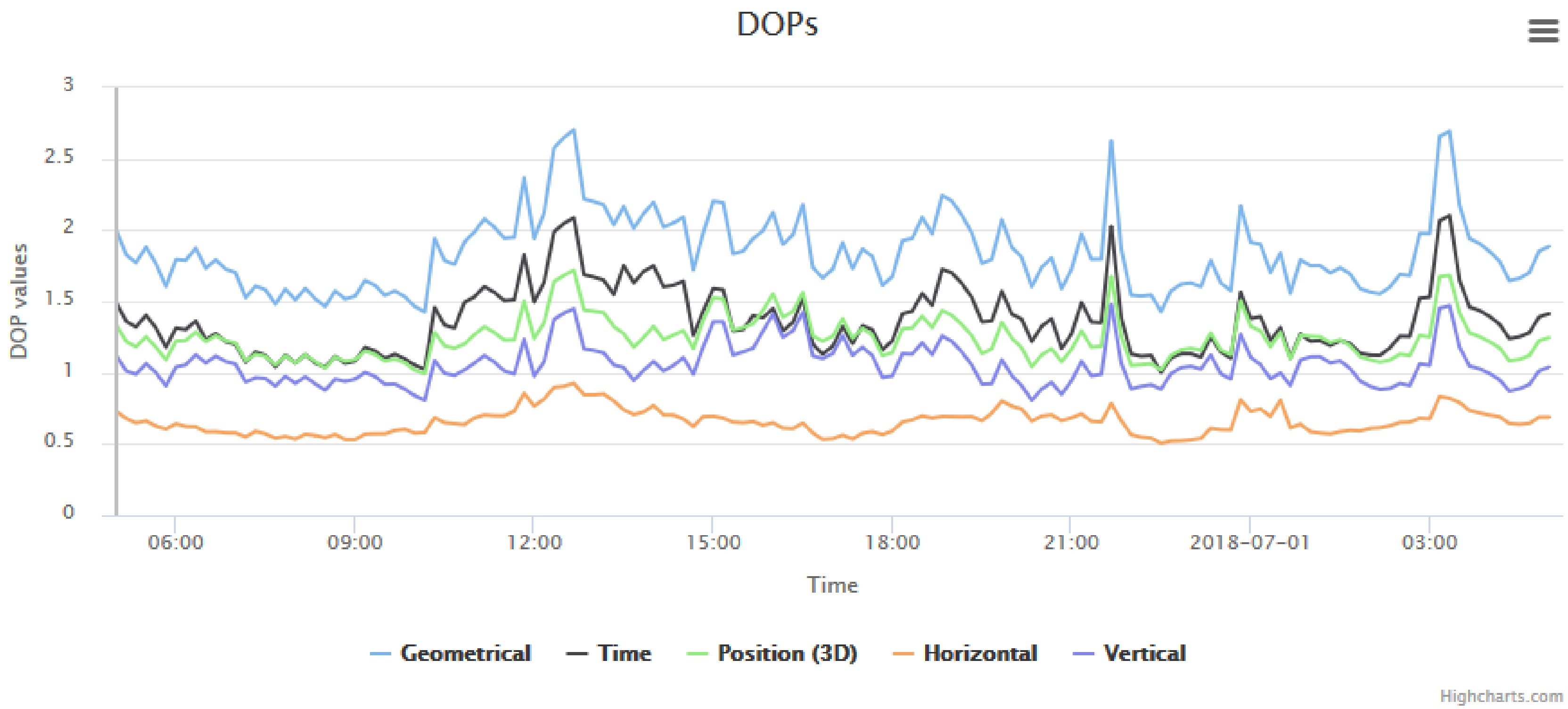
Appendix A: Trimble Differential Correction Summary

Site Number(s)	Total Positions	% Coverage	% code corrected by post-processing (number)	% Carrier corrected by post-processing	% code position chosen over carrier	Accuracies (% of corrected)						
						5-15cm	15-30cm	30-50cm	0.5-1m	1-2m	2-5m	>5m
2, 3, 6, 7*	167	50	91.62 (153)	33.53	92.86			26.80	7.19	49.02	16.99	
1	86	100	100 (86)	100	100		12.79	83.72	3.49			
5	87	95.40	95.40 (83)	13.79	75.00				7.23	55.42	37.35	
4	76	100	100 (76)	100	6.58	90.79	2.63	6.58				

*site data collected individually, 4 data files corrected simultaneously with one output.

Appendix B: Trimble Satellite Planning Graphs




DOPs
DOP values
3
2.5
2
1.5
1
0.5
0
06:00
09:00
12:00
15:00
18:00
21:00
2018-07-01
03:00
Time
Geometrical
Time
Position (3D)
Horizontal
Vertical
Highcharts.com