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Location Gathering: An Evaluation of Smartphone-Based Geographic Mobile Field Data Collection Hardware and Applications

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LOCATION GATHERING:
AN EVALUATION OF SMARTPHONE-BASED GEOGRAPHIC MOBILE FIELD DATA COLLECTION HARDWARE AND APPLICATIONS

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Master of Arts

by

Joel A. Clark

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AN EVALUATION OF SMARTPHONE-BASED GEOGRAPHIC MOBILE FIELD DATA COLLECTION HARDWARE AND APPLICATIONS

by

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APPROVED FOR THE DEPARTMENT OF GEOGRAPHY AND GLOBAL STUDIES

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ABSTRACT

LOCATION GATHERING: AN EVALUATION OF SMARTPHONE-BASED GEOGRAPHIC MOBILE FIELD DATA COLLECTION HARDWARE AND APPLICATIONS

By Joel A. Clark

Mobile field spatial data collection is the act of gathering attribute data, including spatial position, about features in a study area. A common method of field data collection is to use a handheld computing device attached to a global navigation satellite system in which attribute data are directly inputted into a database table. The market for mobile data collection systems was formerly dominated by bulky positioning systems and highly specialized software. However, recent years have seen the emergence and widespread adoption of highly customizable and user-friendly mobile smartphones and tablets. In this research, smartphone devices and smartphone data collection applications were tested and compared to a conventional survey-grade field data collection system to compare the capabilities and possible use cases of each. The test consisted of an evaluation of the accuracy and precision of several mobile devices, followed by a usability analysis of several contemporary data collection applications for the Android operating system. The results of the experiment showed that mobile devices and applications are still less powerful than dedicated conventional data collection systems. However, the performance gap is shrinking over time. The use cases for mobile devices as data collection systems are currently limited to general use and small to mid-size projects, but future development promises expanding capability.

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Introduction

People use geographic field data collection for a variety of reasons. Student and professional research, surveying, government agencies, statistical collection, environmental science, and business are just some of many applications. Digital geographic data acquisition also forms the backbone of Geographic Information Systems (GIS). Given all the potential applications, users have much incentive to try to employ data collection hardware for projects. However, conventional survey-grade digital geographic data collection systems are expensive, bulky, and highly specialized. Given the constraints, many users would likely prefer pen and paper analog methods. In recent years, however, the smartphone revolution has changed the face of geographic data collection. Average United States citizens now have access to, and are likely to carry, powerful, portable, handheld computers that are highly adaptable and customizable. The proliferation of mobile smartphone technology has given users the ability to perform geographic field data collection.

Limitations exist for using smartphones for geographic field data collection. Smartphone technology is still in its infancy. Application developers saturate the smartphone application markets with a constant stream of new applications, many without rigorous quality testing (Gray, 2014). Smartphone devices can enter and leave the market in less than a year without time for users to acquire comprehensive experience. Meanwhile, conventional digital geographic collection systems have existed in progressively improving form for several decades (Gakstatter, 2009). While conventional systems are not as accessible and convenient, they are well tested, accurate, and considered industry standard. Smartphones and smart tablets, however, have widespread use, and users have grown accustomed to their conveniences. Many companies and agencies have adopted bring-your-own-device (BYOD) policies in recent years, encouraging employees to bring and utilize their own devices at work (Gartner, 2013). The surge of “smart” device technology and the variety of useful applications available will certainly drive users to use smartphones and personal tablets instead of conventional systems for collecting field data. Given the recent proliferation and advancements of mobile technology, can smartphones address similar use cases to conventional survey-grade systems for geographic field data collection?

Literature Review

Geographic Data

GIS data collection. GIS relies on digital geographic data. GIS can provide advanced querying, displaying, and problem-solving capabilities for spatial datasets. Many methods can be used to create GIS data, for instance air photo digitizing, historic map digitizing, and satellite image classification. One of the most prolific and straightforward methods, however, is to send staff out into the field to map features and note attributes. Features can be field-mapped in a variety of ways, including the simple and inexpensive method of making hand-drawn and annotated maps and manually digitizing the maps back at the office (Baker & Gaspard, 2007). However, digital technology has made possible the collection and digitization of geographic data while in the field, greatly speeding the collection of GIS data.

Trimble Ltd. pioneered digital geographic field data collection. In 1978 Charlie Trimble and two others broke away from Hewlett Packard to develop navigation products in Los Altos, California. Trimble purchased undeveloped GPS receiver technology from Hewlett Packard and developed it, eventually releasing the world's first commercial GPS survey products in 1984. After many successful acquisitions and developments, Trimble has since become the industry leader in GPS-based surveying hardware and digital geographic data collection systems (Trimble Navigation Limited, 2015). The hardware and supporting software marketed by Trimble and similar survey-grade products made by competing companies comprise the conventional digital data collection systems referred to in this research.

Mobile data collection systems. The primary concern for geographic mobile data collection systems (MDCS) is the ability to collect accurate spatial and descriptive information. Descriptive information entry, which will be looked at in more detail later, involves the input of attribute information into an application on a handheld computing device to be stored in a database (Jung, 2011). Spatial information, meanwhile, is typically stored as coordinates. Other methods for describing location exist, but in our current digitally oriented paradigm, numeric coordinate data are the most prolific (National Wildfire Coordinating Group, 2007). Global navigation satellite system (GNSS) positioning is the most widely utilized method for collecting numeric coordinates. GNSS chipsets are onboard most mobile phones and tablets, and are used by applications for coordinate data acquisition. GNSS has a number of problems regarding accuracy, which are especially pronounced in smartphones. Efficient information entry and accurate GNSS capabilities are essential to effective MDCS.

GNSS

How GNSS works. GNSS operates using a constellation of satellites in orbit around the Earth. A receiver on the surface of the Earth, typically held by or positioned near the user, receives radio signals from each satellite in view. The time of transmission between each satellite and the receiver is found. The time of transmission is used to calculate the distance between the receiver and the satellite. Knowing the distance between the receiver and the satellite narrows down the possible location of the receiver relative to the satellite. If, for example, a satellite is 11,000 miles from a receiver, then the receiver must be, logically, somewhere on a sphere of 11,000 mile radius surrounding the satellite. After creating at least four distance spheres around four different satellites, the intersection point between the four spheres can be calculated to determine the position of the receiver (Hurn, 1989). The basic principle of how GNSS operates has not changed much since its creation; major advancements, however, have been made in accuracy, availability, reliability, and speed.

GNSS around the world. Several independent GNSS constellations currently exist. GPS is the system operated by the United States. GPS was the first fully operational GNSS, and, as a result, the acronym GPS is often used by the general public to refer to GNSS broadly. GLONASS, or “GLObal NAvigation Satellite System,” is a fully operational GNSS provided by Russia (Hofmann-Wellenhof, Lichtenegger, & Wasle, 2008). Other GNSS nearing completion are the European Union’s Galileo system, China’s BeiDou system (known as BDS or COMPASS), India’s Indian Regional Navigation Satellite System (IRNS), and Japan’s Quasi-Zenith Satellite System (QZSS). New consumer GNSS receiver chips, including those found in smartphones, increasingly support multiple GNSS, once a feature only found in professional systems (Segan, 2011). Support of multiple GNSS increases the amount of visible satellites to a receiver at a time, and thus can improve accuracy and reliability.

Impediments to GNSS. Many factors affect the accuracy of GNSS, in smartphones or any receiver. Typically an inaccurate reading is caused by failures of several types and not one particular event. Earth Measuring Consulting (2005) states that the following affect the accuracy of GNSS:

- Technique employed (i.e. autonomous, assisted, differentially corrected)
- Surrounding conditions
- Number of satellites in view
- Satellite geometry
- Distance from reference receiver(s) (for differential correction)
- Ionospheric conditions
- Quality of GNSS receiver

The most optimal conditions for GNSS accuracy, as stated by Earth Measuring Consulting (2005), are “a clear view of the sky with no obstructions from about 5 degrees elevation and up.” Other contributors to error include solar coronal mass ejections, plate tectonics, and basemap quality. Smartphones in particular can have limitations to accuracy depending on the specific application used, as developers may decide to truncate the decimal precision of readings or may program long intervals between position retrievals. Users should be fully aware of the numerous causes of error and attempt to control conditions as well as possible.

Geographic reference frames. GNSS users may encounter many spatial reference frames, but smartphones are often limited to only one. A spatial reference frame is a simplified model of the earth's surface which is used to reference the placement of coordinates in a coordinate system. Global navigation satellite systems operate using the latitude and longitude coordinate system, however, the default output spatial reference frame could vary between receivers. Two reference frames commonly encountered when working with collection data in the United States are North American Datum 1983 (NAD83) and World Geodetic System 1984 (WGS84). Professional data collection, in the United States, often uses NAD83 as the reference frame for storing positions (Gakstatter, Dennis, Kelly, & Greenwald, 2013). However, most consumer GNSS chipsets typically employ WGS84 (Snay & Soler, 2000). Smartphones applications in particular use WGS84, typically without an option to change. Converting WGS84 coordinates to NAD83 coordinates may be required to implant smartphone-collected data into existing datasets. However, transformations between two coordinate systems introduce positional error, which may fluctuate depending on the location, but are typically between one and seven meters (Gakstatter et al., 2013). The geographic reference frames employed by smartphones can be an unexpected and unwanted source of positional error.

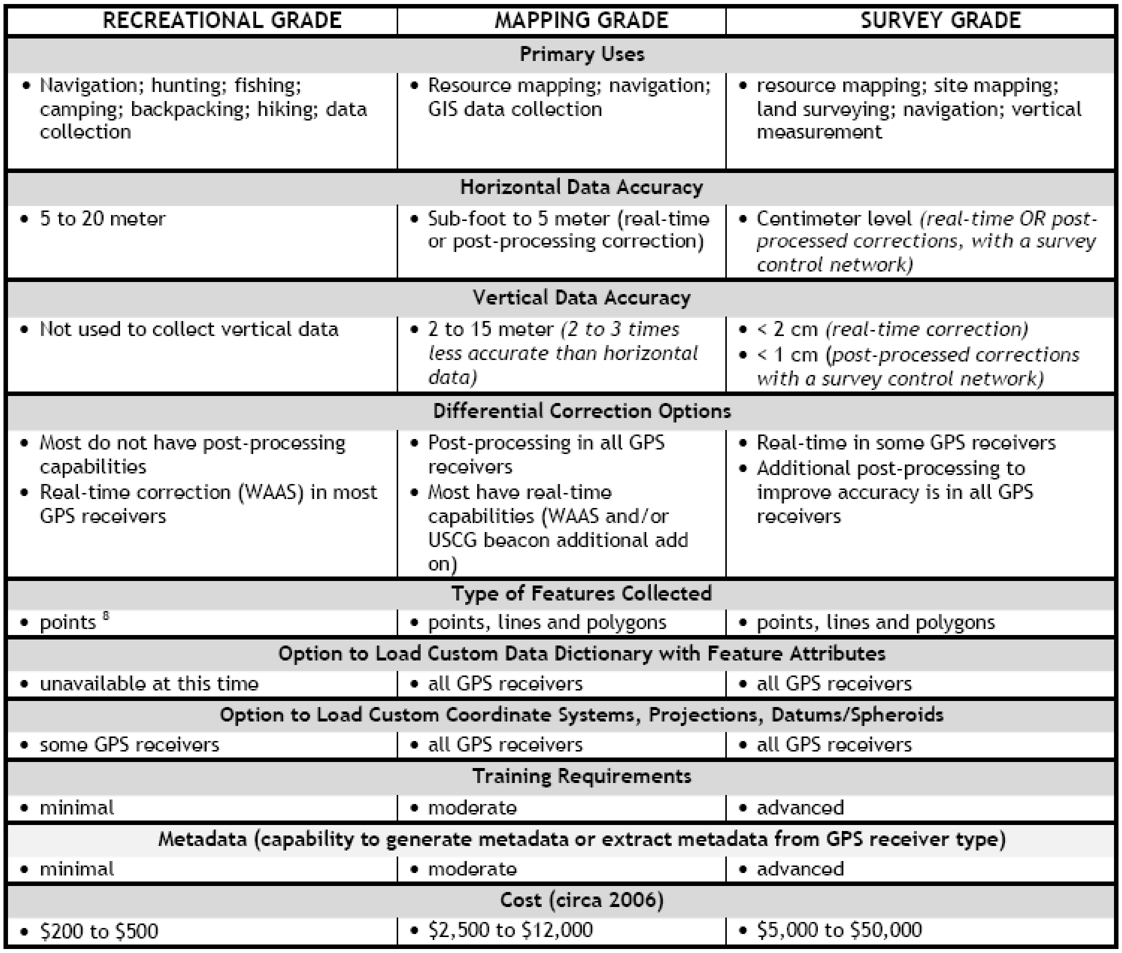
NMEA standard for GNSS. Consumer GNSS units, especially smartphones, output data to software using the NMEA 0183 standard. NMEA stands for the National Marine Electronics Association, which is a United States-based trade organization that sets standards for marine electronics. The NMEA 0183 standard uses a simple ASCII serial communication protocol to transmit data. ASCII, which stands for the American Standard Code for Information Interchange, is a set of standardized character symbols for use in digital encoding. NMEA 0183 is a straightforward protocol for transmitting data (Betke, 2001). The simplicity of the standard allows for programmers to easily integrate GNSS into many applications and has thus contributed to its widespread use in recreational GNSS. Survey-grade GNSS receivers, however, typically support several different protocols for data transmission which can be quite complex. Trimble's TSIP format, for example, provides more detailed information to the receiver than does NMEA (Trimble Navigation Limited, 2000). The exclusivity of NMEA as the protocol for smartphones allows for ease of development, but limits options for use of more intricate protocols.

GNSS augmentation. Numerous techniques exist for improving GNSS accuracy. Different GNSS receiver chipsets are capable of employing different correction techniques. Many GNSS chipsets, including those in some smartphones, have correction techniques built-in (Chen & Guinness, 2014). SBAS, or Satellite-Based Augmentation System, also called differential correction, is an often-used correction technique that employs a large network of base stations that send correction information back to the satellites to be sent to receivers. SBAS is capable, depending on which network is used and the quality of the receiver, of improving GNSS accuracy to the sub-meter level. RTK, or real-time kinematic, is another form of correction that works similarly to SBAS, but compares the carrier waves of transmission signals rather than positional data. RTK is capable of very accurate and reliable results and is often found on professional equipment (Mekik & Arslanoglu, 2009; Gakstatter, 2014). PPP, or precise point positioning, is a technique that does not use any base stations, but instead uses highly accurate clocks and almanacs to exactly locate receivers. PPP is currently increasing in use and some new consumer GNSS products support it (Murfin, 2013). Correction-enabled GNSS chipsets allow considerably more accurate data collection.

GNSS chipsets. Several GNSS chipsets exist on the market and can be found both in smartphones and conventional systems. A GNSS chipset is the physical microchip that collects GNSS signals from satellites. While thousands of consumer GNSS-enabled products exist on the market, only a handful of GNSS chipsets exist (Gakstatter, 2013). Manufacturers of popular consumer GNSS chipsets include SiRF Technology Incorporated, MediaTek Incorporated, SkyTraq Technology Incorporated, u-blox Holding AG, Broadcom Corporation, and a few others (Canada GPS, 2010). Many smartphones, for concerns of space, integrate GNSS and other functions into a central multi-purpose chip in a technique called system-on-a-chip (SoC) technology (Smith, 2012). SoC uses the smartphone’s miniaturized antenna for collecting GNSS signals, which, due to human body interference and receptivity, can limit accuracy compared to the large antennas used by conventional systems (Rao, Kunysz, Fante, & McDonald, 2013). Most consumer GNSS receivers differ in terms of built-in features and appearance, but accuracy and precision behavior is almost completely dependent on chipset hardware. Therefore, when concerned about accuracy and precision, a user should investigate the product's datasheet for specifics about the GNSS chipset.

Types of GNSS units. GNSS receiver chipsets come in different grades. Different sources classify the types and capabilities of GNSS chipsets a little differently, but units are often sorted into three categories: low accuracy recreational grade (greater than 15 m accuracy), mapping grade (less than 15 m and greater than 1 m accuracy), and very precise survey grade (less than one meter accuracy). The capabilities of the grades of GNSS can be seen in Table 1. Some professional GNSS modules can achieve sub-meter accuracy, whereas many smartphones typically achieve 10 m accuracy (Zandbergen, 2009). However, most smartphones can accept bluetooth-tethered GNSS receivers of better grades (Wing & Eklund, 2007). Tethering better quality external receivers can therefore improve the accuracy of a smartphone and expand potential use cases. GNSS unit grades allow for quick comparison between device capabilities.

Table 1. Comparison of the different grades of GNSS units



RECREATIONAL GRADE	MAPPING GRADE	SURVEY GRADE
Primary Uses		
• Navigation; hunting; fishing; camping; backpacking; hiking; data collection	• Resource mapping; navigation; GIS data collection	• resource mapping; site mapping; land surveying; navigation; vertical measurement
Horizontal Data Accuracy		
• 5 to 20 meter	• Sub-foot to 5 meter (real-time or post-processing correction)	• Centimeter level *(real-time OR post-processed corrections, with a survey control network)*
Vertical Data Accuracy		
• Not used to collect vertical data	• 2 to 15 meter *(2 to 3 times less accurate than horizontal data)*	• < 2 cm *(real-time correction)* • < 1 cm (*post-processed corrections with a survey control network)*
Differential Correction Options		
• Most do not have post-processing capabilities • Real-time correction (WAAS) in most GPS receivers	• Post-processing in all GPS receivers • Most have real-time capabilities (WAAS and/or USCG beacon additional add on)	• Real-time in some GPS receivers • Additional post-processing to improve accuracy is in all GPS receivers
Type of Features Collected		
• points[8]	• points, lines and polygons	• points, lines and polygons
Option to Load Custom Data Dictionary with Feature Attributes		
• unavailable at this time	• all GPS receivers	• all GPS receivers
Option to Load Custom Coordinate Systems, Projections, Datums/Spheroids		
• some GPS receivers	• all GPS receivers	• all GPS receivers
Training Requirements		
• minimal	• moderate	• advanced
Metadata (capability to generate metadata or extract metadata from GPS receiver type)		
• minimal	• moderate	• advanced
Cost (circa 2006)		
• $200 to $500	• $2,500 to $12,000	• $5,000 to $50,000

Note. Adapted from global positioning system (GPS) data collection guidelines, p. 12, by Suffolk County, New York, 2008.

Smartphone positioning. Most applications are designed to make use of the internal location finding services in a smartphone device. Location finding is provided for a mobile phone through one or all of three methods, GNSS, Wi-Fi, or cellular triangulation. Most mobile devices contain a GNSS chip. GNSS is typically augmented, depending on the device, with cellular triangulation and Wi-Fi fingerprinting. GNSS on smartphones is enhanced to speed satellite acquisition times. The enhanced GNSS is known as assisted GPS or A-GPS (Zandbergen, 2009). A-GPS greatly speeds the time to fix by approximating the receiver's location while simultaneously pre-downloading the necessary GNSS almanacs over the carrier's network (SkyTel, 2004). Positional approximation methods like Wi-Fi fingerprinting and cellular triangulation can also function with reduced accuracy, on many devices, independently of the GNSS chip with GNSS turned off. In order to fully utilize the location finding abilities of a smartphone, a user should activate all location services.

Wi-Fi fingerprinting and cellular triangulation enhance smartphone positioning. To create a Wi-Fi fingerprinting service, a vehicle equipped with a Wi-Fi receiver and a GNSS unit is routed through an area. A GNSS location along with the signal strength and addresses of local Wi-Fi signals are recorded to a database at intervals along the route. When a consumer's mobile device activates Wi-Fi positioning it measures local Wi-Fi addresses and signal strengths and compares them to the database, matching the device with the closest fingerprinted location. Cellular triangulation finds a device's position by triangulating the signal strength of three or more cellular transmission towers with the cellular device, and calculating an approximate location (Zandbergen, 2009). The extra options available to smartphones to find locations offer some adaptability to overcome the shortcomings of limited GNSS chipsets.

GNSS testing and error reporting. Field-testing GNSS chipsets is necessary to properly understand data collection performance. Particular devices should be field tested in the conditions and environments intended for use (Hayakawa & Tsumura, 2008). The Federal Geographic Data Committee provides a standardized methodology for reporting horizontal and vertical accuracy in GNSS receivers. The National Standard for Spatial Data Accuracy (NSSDA) formed by the Federal Geographic Data Committee, does not recommend any particular level of accuracy for devices, and instead suggests that users determine what level is appropriate. The Federal Geographic Data Committee (1996) states the data standard for reporting horizontal accuracy as the following: "The reporting standard in the horizontal component is the radius of a circle of uncertainty, such that the true or theoretical location of the point falls within that circle 95-percent of the time." The federal standard is beneficial for reporting accuracy when field testing devices.

GNSS accuracy error can be described in different ways. Error is defined as the level of diversion from a true value (Gong, Zheng, & Chen, 1995). The typical method for calculating error values is Root Mean Square Error (RMSE), which is recommended by the NSSDA. RMSE is calculated by taking the square root of the average of the square of the total error. However, Zandbergen (2008) argues against using RMSE for non-normal distributions, or datasets with significant outliers. RMSE amplifies large errors by generally measuring the magnitude of error. Another type of error calculation is Circular Error Probable (CEP). CEP was developed by the military for measuring the accuracy of projectiles; it establishes a circle of distance in which at least 50% of all fired projectiles are expected to land (U.S. Army Intelligence Center, 1987). Some GNSS manufacturers now use CEP as a means to calculate and advertise positional error. Mean or average error is another commonly used method, which is a simple average of the diversion from the true value (Zandbergen, 2008; Gong et al., 1995). For a small point sample size average error is the easiest to employ.

Precision vs. accuracy. Precision is another aspect of GNSS that is different from accuracy, and can affect data collection. Precision is important in mobile phone coordinate collection because applications are often limited in precision based on programming. Accuracy of a GNSS device is the closeness of a coordinate reading to the actual coordinate location of the system. Precision of a GNSS device is the closeness of a coordinate reading to the mean of several observations. An accurate GNSS will place a point close to where it should be, and a precise GNSS will repeatedly place a point close to the same location that it placed last time (Earth Measurement Consulting, 2005). A GNSS device that is using a small number of decimal places to store coordinate data, for example, may have the effect of appearing precise, while simultaneously being very inaccurate. Smaller decimal precision limits the area in which a point can be placed, effectively forcing point locations into a grid pattern (Zandbergen, 2009). Device precision is just as important as average accuracy when measuring GNSS receiver capabilities.

Methods for collecting data. GNSS is not the only technique for obtaining coordinate data. Another technique is the use of the on-screen heads-up method. In heads-up, a user brings a device to the field that displays the local environment to the user, often in the form of airphotos or basemaps. The user selects his or her position by comparing the visually presented map data on the device to his or her surroundings. The user can then enter information about the identified feature. Heads-up is less expensive than using GNSS as it does not require any GNSS hardware. Furthermore, a skilled user can often site positions with great accuracy that would otherwise require very complex and expensive GNSS hardware.

Heads-up digitizing has limitations. Heads-up is only as effective as the skill of the user or the accuracy and detail of the available basemap (U.S. Fish and Wildlife Service, 2009). Heads-up requires identifiable landmarks for the user to locate the feature relative to other features in the basemap. Furthermore, heads-up requires that the user focus more attention on the general environment and the device and less on his or her immediate environment, which produces a safety as well as time management issue. Heads-up offers an alternate, though more problematic, means for a user to find a position while using a mobile application.

A further extension of heads-up is a hybrid between on-screen position choosing and GNSS, sometimes called GNSS-assisted heads-up. In the hybrid approach a user employs a basic GNSS receiver to locate himself or herself on the basemap, but the user finishes the final placement of the coordinate. The approximate location provided by the GNSS can speed the time the user spends placing a location and reduces the limitations of heads-up. Smartphones lend themselves well to the heads-up collection method because they employ sensitive and highly interactive touchscreens. Allowing heads-up is a way in which an application developer can potentially increase user accuracy without having to fundamentally change how the application interacts with the smartphone's GNSS hardware.

Data Entry and Management

Data management success. The success of a geographic data collection project is only partly determined by positional accuracy. While a project will be jeopardized by inaccurate positional data, poorly entered and managed attribute data will also result in project failure. The GNSS element and data-entering element function as one unit, which comprises the MDCS. Data entry is the second necessary component. Data entry is affected by different concerns than coordinate acquisition, such as software quality and user interface issues. Many software and application options are available on the market. Choosing the appropriate solution for a particular data collection project can be challenging.

Collection device applications. Data entry applications for smartphones and conventional MDCS differ. Smartphone applications are usually relatively simple, fast, and intuitively designed for broad audiences, but their simplicity limits project flexibility. Conventional systems are typically complex, difficult to learn, but powerfully adaptable to project requirements. Considerable research and development improved performance of conventional systems, making them formidable data collectors (Van Elzakker, Delikostidis, & Van Oosterom, 2008; Moe, 2004; Jung, 2011). However, conventional MDCSs usually come at a high cost, with typical hardware software bundles reaching $5,000 to $50,000. Common examples of data collection software are ArcPad, Pendragon, and Field Assets (Department of Defense, 2010). Mobile phone applications are much less expensive. Many applications are free, but some specialized applications require either a one-time fee or a subscription (Fleishman, 2010). The applications that can be obtained for mobile phone devices are also of diverse quality. Application development in the mobile world is not well regulated or industry reviewed, and significant application changes and updates are frequent. Conventional applications are well-used systems, which may be difficult to match in quality by smartphone applications.

Mobile phones have limitations, but they are highly versatile which make smartphone applications a tempting choice for data collection. Mobile phone platforms provide MDCSs additional features over a conventional system for use in the field. Smartphones have the advantages of small portable size, SMS messaging, internet access, email access, camera support, immediate upload of results, and of course phone service (Mourão, 2010). Mobile phones are, however, limited in terms of memory, screen size, and battery life. Mobile phones also depend on mobile networks, which have variable performance in different regions and environments (Moe, 2004; Mourão, 2010). However, the powerful capabilities and the convenience of preexisting ownership provides users ample incentive to use mobile phones for collection. Many tradeoffs exist between conventional and smartphone-based collection applications, and a user will need to decide on the most appropriate option for the task.

Effective software design is one of the major elements of a usable MDCS. Noting the amount of technical expertise required for software use is important, especially before installation and when planning ongoing data management (Jung, 2011). The user interface should be highly intuitive for users with limited skills. High rates of expected user interaction requires an interface that is designed for simplicity. Fieldwork distracts the user, so the interface should demand a minimal amount of user attention. The high volume of data entry means the user should be able to enter data quickly and efficiently. The probability for entering erroneous data in the field is high, so the interface should be designed to quickly recover from entry errors or prevent them altogether. Finally, to be most useful for geographic projects, data should be saved in a format that is accessible by a standard GIS system (Moe, 2004). A well constructed application is a necessary component of an effective MDCS.

Usability testing. Applications can be tested to determine the usefulness to a user's project needs. Applications are often tested using a technique called usability testing. Usability testing is a procedure in which the effectiveness of user interaction with software or websites is evaluated. Instead of measuring theoretical interaction, usability testing measures real-world interaction with real users. Testers must identify the target audience for the software before the usability test. A sample group from the target audience is gathered. Tasks and questions are given to the users in order to discover the ability of the users to complete important tasks with the application. Establishing clear success criteria is very important to develop constructive results (Wiberg, 2003). Creating usability tests to evaluate performance will improve the quality and usefulness of software.

The most straightforward usability methodology is to implement a criteria-based summative evaluation. Summative evaluation applies overall rankings to the usability of an interface (Roth & Harrower, 2008). Usability is typically rated using a measure of five attributes: learnability, efficiency, memorability, error rate, and satisfaction (Wiberg, 2003). Furthermore, the effectiveness of a user interface can be further evaluated by calculating the information-to-interface ratio, which is a measure of how much screen space is occupied by interface content (Harrower & Sheesley, 2005). Some attributes like efficiency, error rate, and information-to-interface ratio can be measured empirically. Other attributes like learnability, user retention, and satisfaction are complex and require more detailed psychological analysis of subjects. Overall, a criteria-based summative evaluation provides an effective means for discovering software usability.

Literature Summary

Positional accuracy and reliable information collection make up the core of a respectable MDCS. Incorrect positions can deeply compromise a geographic data collection project, as the ability to show where a feature is located is of great concern. Further, providing quality attribute data is also of importance. Without knowing what is at a location, the spatial information is essentially useless. User-friendly data collection software is important for successful projects. Without user-friendly and reliable software, the collection of data will be too difficult and discourage users. Accuracy and usability are essential components to profitable MDCS.

Methodology

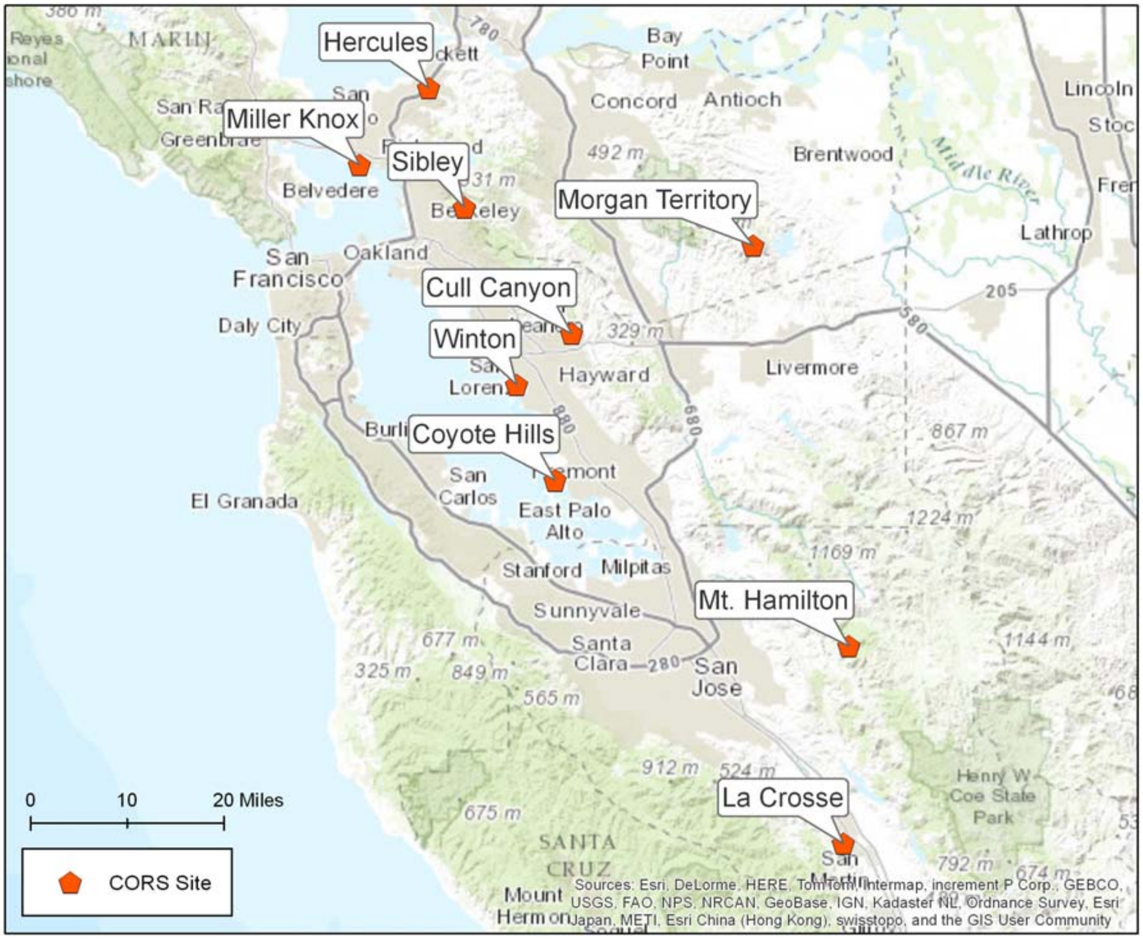
A dual experiment was devised to evaluate the effectiveness of smartphone-based MDCS. The evaluation was designed to test the accuracy of smartphone GNSS chipsets and the usability of smartphone spatial data collection applications, and compare these to a conventional system. The evaluation was divided into two distinct experiments. In the first experiment, several GNSS chipsets were tested to find horizontal accuracy and precision. Positional accuracy is often a chief concern when conducting field data gathering, and knowing if any common chipsets perform particularly better than others in certain environments is essential. In the second experiment, several popular smartphone applications were field tested and evaluated for usability with an established set of criteria. The quality of data gathering applications is also of chief concern when field data gathering. Understanding how many applications are capable of providing acceptably high usability is necessary. In both experiments, a survey-grade conventional system performed the same routines as the smartphone systems for comparison. The goal of the pair of experiments was to find how significantly typical smartphone chipsets and applications vary in quality, and to see how significantly chipsets and applications contrasted to a conventional survey-grade system.

Accuracy and Precision Experiment

The GNSS positional accuracy experiment consisted of several steps. In the first step, locations were chosen for performing accuracy tests. Secondly, several devices were chosen with which to test. At each location the devices collected points at intervals. Finally, the points collected were compared to detect differences in positional accuracy and precision.

Test locations. Survey monuments were a first solution for test locations, as they are known positions with carefully surveyed latitude and longitude. However, investigation revealed that survey monuments had a number of drawbacks. First, survey monuments are marked on the ground using small brass disks. More often than not, the disks were missing or difficult to locate. Secondly, survey monuments were often surveyed several decades past and not updated frequently, and thus they use older reference frames like NAD83 1st iteration. Comparing NAD83 1st iteration to the standard GPS reference frame of WGS84 4th iteration can result in several meters of offset, especially in California and other tectonically active areas (Gakstatter et al., 2013). Therefore, survey monuments were not considered desirable as test locations, given that the experiment should be capable of detecting submeter accuracy.

Continuously operating reference stations. CORS, or continuously operating reference stations, were chosen for reference benchmarks. The CORS program is a type of RTK system put in place by the United States National Geodetic Survey (NGS) for the purpose of monitoring tectonic shifting. CORS maintains a wide distribution of stations permanently positioned on private land. The location of CORS stations are publicly displayed on an interactive map provided by the NGS website. CORS receivers continuously collect positional coordinates and waveform patterns. The NGS uses the collected data to update the position of the station and continental surface change. CORS uses an up-to-date reference frame for each update (Snay & Soler, 2008), currently NAD83 2011. Unlike monument disks, CORS sites contain physically significant and actively maintained equipment, and thus are easy to locate in the field. CORS sites were obtained from the NGS website using an interactive map. Antenna location coordinates were found on accompanying datasheets. The sites chosen were around the San Francisco Bay Area and can be seen in Figure 1. CORS sites make excellent positional benchmarks for research.



Sources: Esri, DeLorme, HERE, TomTom, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, and the GIS User Community

Figure 1. Map of accessible San Francisco Bay Area CORS sites

Devices. Eight smartphone and bluetooth tetherable devices were selected for the GNSS test. A conventional Trimble survey system was also included in the device test for comparison. Four of the tested devices were smartphones, and four of the devices were bluetooth tetherable GNSS. Bluetooth tetherable units were included in the experiment because they theoretically provide an easy means to access better quality GNSS from a smartphone platform. Different commonly found GNSS chipsets were within the chosen devices, which can be seen in Table 2. Furthermore, the age and quality of the devices also varied. Dissimilarity of the devices allowed for a broad comparison of different chipsets, quality, and ages.

Table 2. List of devices tested

Type	Device	Grade	Channels, GNSS	Onboard GNSS Chipset
Smartphone	Apple iPhone 4	Recreational	24, GPS	Broadcom BCM4750IUB8
	Motorola Droid X MB810	Recreational	20, GPS	Texas Instruments NaviLink 3.0
	Kyocera Rise C5155	Recreational	20, GPS	Qualcomm QTR8615
	LG Volt LS740	Recreational	50, GPS/ GLONASS	Qualcomm gpsOne Gen 8a
Bluetooth Tethered Module	TomTom GPS Mk.II	Recreational	20, GPS	SiRF Star III GSP3f 7851
	Qstarz 818x	Mapping	66, GPS	Mediatek MTKII
	Dual XGPS 150A	Mapping	65, GPS	SkyTraq Venus638LPx
	Bad Elf GNSS Surveyor BE-GPS-3300	Mapping	56, GPS/ GLONASS	u-blox NEO-7P
Survey Positioning System	Trimble Pathfinder ProXRT w/ Zephyr 2 Antenna	Survey	220, GPS	Trimble Maxwell 6 GNSS

Procedures. Positional accuracy was tested at each site. Each device was activated and points recorded. Smartphones were used with all assisted location settings turned on to improve time-to-fix. Each device gathered 120 points while stationary at 1-second intervals. The process was repeated until all points were gathered for all devices at each site. In the event that a CORS antenna location could not be reached due to obstructions, a stake was placed in the ground. The offset distance and bearing of the stake relative to the antenna was carefully measured and recorded to factor into later calculations, and the stake used as the benchmark location. The positional accuracy data was used for the concluding calculations.

Positional accuracy and precision were calculated for all devices at all sites. The data from all devices were loaded into ESRI's ArcMap desktop software. The accuracy of the devices was calculated by measuring the distance between the points and the benchmark for each device. The distance measurements were made using the "generate near table" tool found within ArcMap's analysis tool set. The distance measurements were averaged for each device at each site to develop accuracy figures. Precision of the devices was calculated by measuring the average distance between the points collected by each device and their geometric mean center, known as a standard distance calculation. The standard distance calculations were made for all points using the "standard distance" tool found within ArcMap's spatial statistics tool set. The standard distance measurements were recorded for each device and then averaged for each site to develop precision figures. The calculations provided a representation of the actual abilities of the GNSS chipsets in the local conditions.

Application Usability Experiment

The application usability experiment consisted of several steps. First, popular mobile field data collection applications were found on the Android App Store. The applications were installed onto a single smartphone device, and each subjected to usability testing. The usability test was also performed on a conventional collection software application for comparison. The usability test was designed to see how well smartphone collection applications perform different tasks.

Finding smartphone applications. The applications chosen were from the Android App Store. The reason for using the Android operating system was that, at the time of project planning, Android offered the greatest variety of collection applications. Furthermore, the varying quality of Android apps, due to the unregulated nature of the Android market, allowed for the widest range of potential application quality a user might encounter. The most popular applications also typically supported all major operating systems, so the importance of a particular operating system quickly diminished. The Android App Store met all the conditions necessary for the experiment.

Search keywords were selected and used to find applications. The phrase “MDCS” is not a very robust search term due to the acronym’s limited use outside of technical and academic papers (Jung, 2011). Chiefly the phrases “GIS” and “collection” offered the most applications that could be considered mobile data collection systems. The application had to, at minimum, provide collection and storage of geographic coordinate data and allow a user to attach descriptive information to collected coordinates to be considered a MDCS. All the applications in the experiment used GNSS to capture coordinates with text and often photos to store descriptive information. The most popular applications, in terms of number of downloads, determined which applications would be tested. The applications found can be seen in Table 3. Twelve MDCS applications were ultimately selected, most with download quantities in the tens-of-thousands.

Table 3. List of applications tested for usability

Application	**Version**	**Downloads**	**Rating**
AnywhereGIS	6.0	100	5.0 (6)
Collector for ArcGIS	10.3	50 Thousand	3.9 (464)
EpiCollect	1.5	5 Thousand	3.7 (61)
Geology Sample Collector	1.0.33	10 Thousand	4.1 (129)
GeoJot+	2.3.17	5 Thousand	3.0 (41)
GeoODK Collect	1.7	1 Thousand	4.6 (29)
Geopaparazzi	4.1.1	10 Thousand	4.3 (125)
Map It – GPS Survey Collector	2.0.0	500	4.4 (17)
MapWithUs 3	3.0.5	5 Thousand	4.0 (24)
MDC GIS	1.5.3	10 Thousand	4.1 (122)
PointGIS	3.0	1 Thousand	4.2 (21)
SuperSurv	3.2.0017	1 Thousand	5.0 (9)
TerraSync (Conventional Application)	5.20	N/A	N/A

Note. Downloads and ratings obtained from the Google Play App Store in January 2015

The applications were loaded onto a LG Volt LS740 smartphone. The smartphone was connected to a 4G LTE Sprint network. The operating system was Android version 4.4.2. The LG Volt is marketed as a mid-level performance mobile phone for the casual user. A LS740 mid-level performance device best approximates an average smartphone a user might employ for applications.

Procedures. The applications were tested for usability. Usability testing is a standard practice in application development, and is designed to assess how easily users can use applications. The usability test methodology as seen in Wiberg (2003) was used, separating tasks into six categories: learnability, efficiency, memorability, errors, satisfaction, and features. Learnability is how easily users can accomplish tasks when using the application the first time. Efficiency is the speed at which a user can accomplish tasks. Memorability is the ability of a user to remember how to use a system after a period of not using it. Errors is the number and severity of errors encountered during use. Satisfaction is how well a user likes using a system. Finally, for this research a category of features was added. The features category summed the number of features included in each application to evaluate the internal diversity of each application. Numerous test categories allows for thorough application usability testing.

The applications were tested for usability using a single human subject, the author of this paper. The performance of each application was assessed in the six categories of usability. The results of each category test were classified into seven classes using the geometrical interval classification method, with one being the least satisfying and seven being the most satisfying. Geometrical interval classification is used for classifying continuous data that is not distributed normally, and is designed to work on data that contains excessive duplicate values, like the results of this experiment (Frye, 2007). The classes were summed for each test category, and the totals compared to determine the test subject's overall usability of the applications.

For learnability, the application was launched for the first time and the user was timed attempting a number of essential tasks. Four tasks were attempted: application setup, time to first point, custom form creation, and data export. The tasks were considered essential operations a user would have to perform to begin using any collection system. Some applications required account creation, which, if present, was included in the setup time. Difficult to learn applications have longer times to initialize tasks than do easy to understand applications. The learnability of each application was reflected in recorded times.

Efficiency was tested by timing point collection. Each application collected ten points at a number of different field sites, and the time to collect each point was recorded. Efficiency reflects the number of gestures and button presses necessary to accomplish the task of collecting a point from start to finish. Wait time at loading screens also affected the efficiency time of each application. Efficient point collection is a significant characteristic of a usable collection application.

Efficiency testing of the applications was done in the field. Three common environments were used for the field test: urban, periphery, and rural. The reason for the different environments was to judge whether the efficiency of each application was affected by the surroundings. Different environments can change the nature of user interaction and, especially with network dependent smartphone devices, also can change the behavior of the device itself. Dense urban areas, for instance, can speed GNSS acquisition time due to A-GPS enhancements from Wi-Fi and cellular coverage, but can overwhelm users with external stimuli. Rural areas often lack Wi-Fi and cellular coverage entirely, which can often cause applications to cease functioning or reduce functionality. Peripheral areas are situated on the edges of cellular and Wi-Fi signal coverage, which can cause intermittent signal loss or very low transmission speeds. Three locations of each type were used. A list of the different field locations can be seen in Table 4, and a map of each in Figure 2. Average efficiency times were recorded for each application.

Table 4. Table of usability efficiency field test locations

Location Name	**Type**	**Data Service**	**Wi-Fi Detected**
Diridon Station	Urban	Strong	Yes
Frank Ogawa	Urban	Strong	Yes
Oakland Library	Urban	Strong	Yes
Clyde Woolridge	Periphery	Low	No
Eden Canyon	Periphery	Low	No
Fairmont Ridge	Periphery	Low	No
Palomares	Rural	None	No
Redwood Park	Rural	None	No
Welch Creek	Rural	None	No

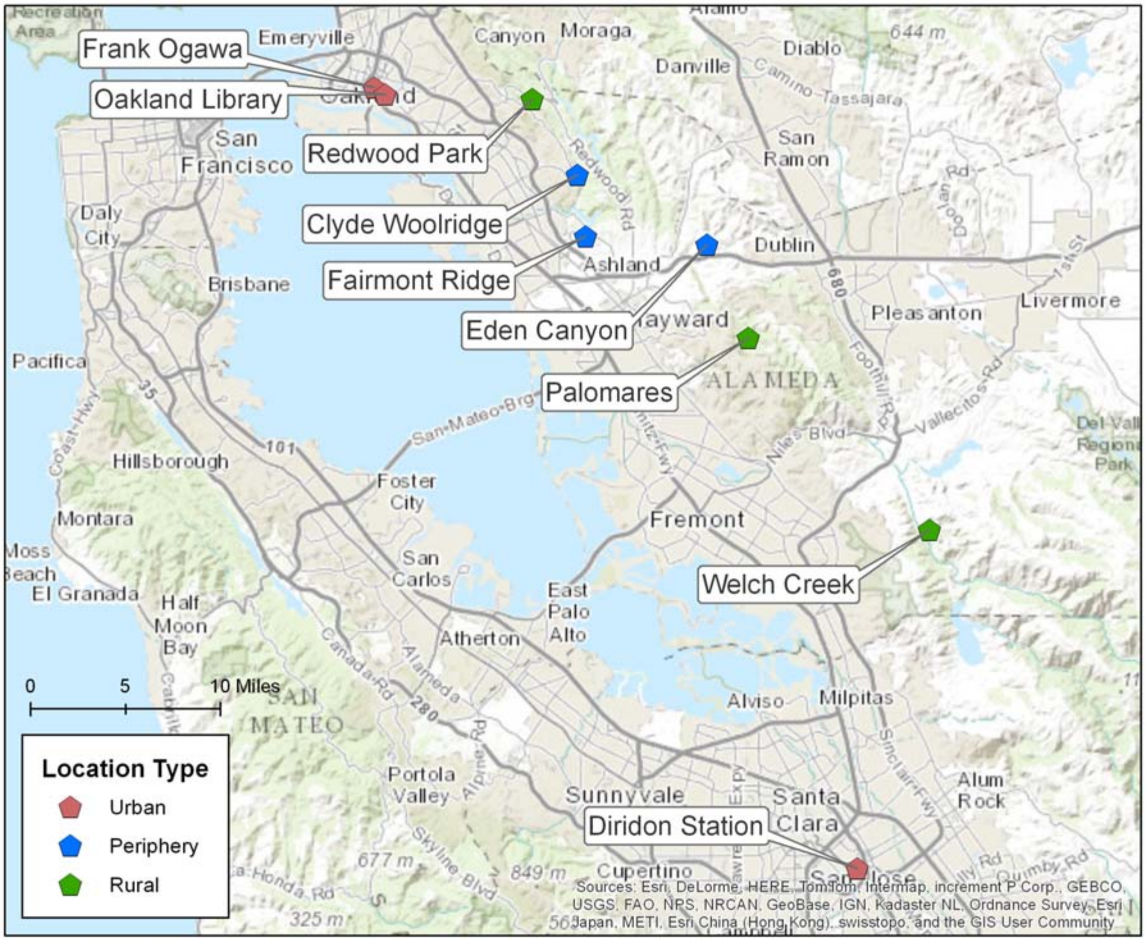


Figure 2. Map of efficiency test locations

Memorability was measured in terms of time between two identical tests. Each application was put through the same tasks as the learnability test once, and then again one month later. The time difference, if any, between the two tests measured the memorability of the applications. The time differences were classified into seven classes, with a time difference of zero considered optimal and successive departure from zero resulting in decreased score. The classifications were summed to produce an overall memorability result for each application.

Error was measured by recording the number of errors encountered during all the other tests. Errors were sorted into two types, simple and fatal errors. Simple errors were application abnormalities that did not cause the application to close. Fatal errors were any error that caused the application to close or require a device restart. Fatal errors were given double weight for the purpose of overall summation. The number of errors and type was noted for each application.

Satisfaction was measured using simple agree or disagree questions. The questions were taken from the established Tullis and Stetson (2004) system usability scale, known for dependable outcomes. The questions used in the ten-item scale can be seen below:

- I think that I would like to use this system frequently.
- I found the system unnecessarily complex.
- I thought the system was easy to use.
- I think that I would need the support of a technical person to be able to use this system.
- I found the various functions in this system were well integrated.
- I thought there was too much inconsistency in this system.
- I would imagine that most people would learn to use this system very quickly.
- I found the system very cumbersome to use.
- I felt very confident using the system.
- I needed to learn a lot of things before I could get going with this system.

The questions were asked about the application and an agree or disagree answer recorded. The overall satisfaction of each application was determined by establishing if the application was able to fulfill the important user goals established by the questions. The number of advantageous answers was totaled for each application.

Each application was explored for different features. Common features found in some or all of the applications were noted and used to prepare the list shown below:

- Camera
- Attach video, audio or other media
- Accuracy display
- Current coordinate display
- Altitude display
- Satellite detail display
- Heads-up capable
- Set user-selected coordinate system
- External/additional sensor support
- Save data to local storage
- Save data to cloud storage
- Show map with current location
- Show map to review collected points
- Cache map for offline use
- Add custom overlays/data (if map shown)
- Change basemap (if map shown)

- Fully customizable forms
- Instant group collaboration
- Edit previous points within application
- Free data export
- Outputs GIS native file types
- Supports multiple data layers

Each application was checked for all of the listed features. If any of the listed features were found present in the application, the application received a mark for that feature. The presence of features was totaled for each application.

The final average times and total instances were compared between all the applications for each category. A seven-value classification was established for each category using the geometrical interval classification method based on the existing range of values in each category, with a class of one indicating the lowest measured performance and seven indicating the highest measured performance. The classes of each category were summed by application. The final sum produced an overall usability value. The resulting usability values were compared between the applications.

Results

Accuracy and Precision Experiment

Accuracy. The accuracy of the tested GNSS devices generally matched their advertised capabilities. Table 5 shows the average for each device at each test location, and the average for each device overall. The Trimble unit had the best and most consistent accuracy performance with an overall average error of 0.74 m with a very low standard deviation. The Bad Elf and the Xgps bluetooth tethered units performed well, achieving 3.78 and 3.82 average error, respectively. However, the standard deviation of the Xgps was less than the Bad Elf, thus displaying more consistent accuracy results between tests. The smartphones and the Qstarz tetherable unit had average errors between five and nine meters, well within the advertised tolerances of smartphone chipsets. The iPhone had the lowest standard deviation of the smartphones, indicating the most consistent results. The Tomtom had the poorest accuracy and had a high standard deviation, indicating the least reliable accuracy performance. Accuracy varied between the devices but generally stayed within the expectations set forth by the receiver grade.

Table 5. Accuracy results, average offset in meters

Device	Coyote Hills	Cull Canyon	Sibley	Hercules	Mt. Hamilton	La Crosse	Morgan Territory	Miller Knox	Winton	Average	Standard Deviation
iPhone	3.66	4.50	2.63	5.76	4.95	6.19	3.43	6.89	7.54	5.06	1.66
Droid X	6.48	7.56	1.16	17.99	12.93	3.53	5.55	2.91	4.18	6.92	5.35
Rise	3.14	6.31	6.07	4.04	8.88	18.47	7.74	13.33	8.46	8.49	4.78
Volt	5.83	5.76	2.83	3.31	6.51	7.96	3.49	2.65	9.19	5.28	2.36
Tomtom	2.48	58.33	12.3	7.14	11.00	7.09	3.48	2.64	12.12	12.95	5.29
Qstarz	3.31	4.79	7.62	4.35	6.63	12.42	6.84	2.85	15.49	7.14	4.25
Xgps	1.54	3.70	3.45	3.77	4.78	3.83	4.11	4.77	4.43	3.82	0.98
Bad Elf	3.35	1.84	6.90	2.79	3.54	7.84	0.78	5.45	1.55	3.78	2.45
Trimble	1.02	0.58	0.24	1.16	0.68	1.20	0.35	0.38	1.10	0.74	0.38

Precision. The precision of the GNSS devices was generally consistent with a few exceptions. The results of the precision test can be seen in Table 6. The Trimble unit, similar to the accuracy test, had the lowest standard distance and the lowest standard deviation between test sites, indicating high precision and reliability. The Bad Elf tetherable unit also had a low average standard distance and a low standard deviation. The Xgps and the smartphones had average standard distances between one and four meters, indicating that each observation was usually within a few meters of the previous. Standard deviation between sites was also similarly low, indicating consistency between test locations. The Qstarz and the Tomtom tetherable units, however, had large average standard distances with very high standard deviations, indicating imprecise and unreliable performance. The Tomtom unit, notably, actually maintained an unnaturally high precision with a standard distance of zero at most sites, but at the Cull Canyon site suddenly had an extreme position fix complication. The polarized results of the Tomtom indicate an inability for the receiver to update position at an acceptable rate and speak of unsophisticated electronics. In general, the performance of most devices displayed an acceptable amount of precision.

Table 6. Precision results, standard distance in meters

Device	**Coyote Hills**	**Cull Canyon**	**Sibley**	**Hercules**	**Mt. Hamilton**	**La Crosse**	**Morgan Territory**	**Miller Knox**	**Winton**	**Average**	**Standard Deviation**
iPhone	3.69	3.45	2.11	3.06	4.29	4.26	2.77	2.72	2.19	3.17	0.81
Droid X	1.13	3.08	0.33	2.59	5.56	3.16	1.33	0.91	0.30	2.04	1.72
Rise	2.20	2.69	0.85	2.60	4.84	7.96	3.95	1.93	1.86	3.21	2.13
Volt	2.32	1.67	1.64	0.90	4.15	3.11	1.48	0.67	1.36	1.92	1.11
Tomtom	0.00	54.37	0.00	0.00	0.00	0.19	0.00	0.00	0.00	6.06	18.12
Qstarz	9.68	1.14	33.90	1.04	2.92	13.40	1.81	0.80	6.71	7.93	10.70
Xgps	1.46	2.16	1.30	3.75	3.31	4.53	2.91	1.17	4.78	2.82	1.38
Bad Elf	1.54	1.02	0.69	0.55	0.89	1.62	0.76	1.21	0.99	1.03	0.37
Trimble	0.21	0.15	0.16	0.07	0.55	0.24	0.68	0.17	0.25	0.28	0.20

Overall. The overall performance of the GNSS devices correlated with the type, age, and cost of the device. The overall performance results can be seen in Table 7. The Trimble unit achieved the best results by a significant margin, which is understandable as the unit is a costly survey system. Of the bluetooth tetherable GNSS units, the two most expensive and newest systems displayed the best performance. Meanwhile, the much older and less expensive bluetooth tetherable systems did not deliver nearly as adequate of results. The older and less expensive Android smartphones have demonstratably inferior quality GNSS chipsets. The newest Android smartphone and the iPhone displayed acceptable GNSS performance. Higher cost and more recent release dates appear to correlate with the overall GNSS performance of the devices in this experiment.

Table 7. Device overall results

Type	Device	Quality	Cost	Release	Accuracy Rank	Precision Rank	Result
Smartphone	iPhone	Recreation	150	2010	13	11	24
	Droid X	Recreation	110	2010	5	10	15
	Rise	Recreation	80	2012	5	6	11
	Volt	Recreation	200	2014	11	13	24
Bluetooth	Tomtom	Recreation	50	2005	3	3	6
	Qstarz	Mapping	90	2007	7	3	10
	Xgps	Mapping	100	2012	15	10	25
	Bad Elf	Mapping	500	2014	13	16	29
Survey	Trimble	Survey	6,000	2008	18	18	36

The results of the GNSS accuracy and precision experiment indicate an increase over time in manufactured GNSS receiver chipset sophistication. The newest chipsets supported GLONASS as well as GPS, effectively doubling the number of satellites available in the constellation. Newer chipsets also supported more signal channels, allowing for increased receiver sensitivity. While the accuracy and precision of recreation and mapping grade chipsets do not compare with conventional survey grade GNSS receivers, the data of the experiment indicates steadily improving technology over time. Modern smartphone GNSS has surpassed the performance of older tetherable GNSS receivers, and is ostensibly approaching the performance level of even contemporary tetherable receivers. The very high cost of conventional systems results in an enormous cost per meter of accuracy gained between smartphones and conventional survey GNSS. Meanwhile, smartphone GNSS still have noteworthy viability for many types of collection projects. Collection projects using a five meter or greater average distance between features, for instance mapping the locations of groves of trees rather than individual trees, could be served quite effectively by a smartphone GNSS. Future development of new high accuracy smartphone and bluetooth tetherable GNSS chipsets will further their acceptability for high-accuracy data collection.

Application Usability Experiment

Learnability. The applications had varying learnability rates. The learnability test results can be seen in Table 8. Most applications required minimal or no setup time upon first use. A notable exception was Collector, which required extensive online account preparation taking several hours. For the purpose of experiment concision all timers were capped at 30 minutes. Most applications had reasonable times for the user to learn how to capture the first data collection point. The creation of input forms was, however, extremely varied. Some applications had very tedious form creation requiring knowledge of markup language, while other applications had simple built-in interfaces.

Finally, the time elapsed for the user to discover how to export data to a desktop computer was logged. Exporting data for some applications was as simple as a button press, while other applications required connecting the smartphone directly to a desktop computer and manually extracting the data. Times were classified using the geometrical interval classification method and summed, in which a larger value indicates a faster to learn system. Overall learnability results were diverse between applications.

Table 8. Application learnability results

Application	Statistic	Setup	1st Point	Form	Export	Sum of Classes
AnywhereGIS	Time	3:58	1:12	4:13	3:20	20
	Score	4	5	5	6	
Collector for ArcGIS	Time	30:00	0:31	25:27	5:24	14
	Score	1	7	1	5	
EpiCollect	Time	0:00	1:09	3:43	0:48	25
	Score	7	5	6	7	
GeoJot+	Time	5:38	0:34	0:47	6:14	21
	Score	3	7	7	4	
Geology Sample Collector	Time	0:58	4:25	12:50	11:53	12
	Score	6	2	3	1	
GeoODK Collect	Time	0:50	0:53	20:42	8:07	17
	Score	6	6	2	3	
Geopaparazzi	Time	0:00	2:33	22:47	3:21	18
	Score	7	3	2	6	
Map It – GPS Survey Collector	Time	0:00	0:33	4:18	6:14	23
	Score	7	7	5	4	
MapWithUs 3	Time	2:21	1:22	9:00	9:50	15
	Score	5	4	4	2	
MDC GIS	Time	3:51	1:09	3:26	5:36	20
	Score	4	5	6	5	
PointGIS	Time	0:00	1:29	30:00	10:31	14
	Score	7	4	1	2	
SuperSurv	Time	1:23	2:04	8:22	11:50	13
	Score	5	3	4	1	
TerraSync (Conventional)	Time	30:00	8:05	4:30	2:46	13
	Score	1	1	5	6	

In the learnability test most of the smartphone applications proved to be more readily learnable than the conventional system. The complexity of the conventional system required much instruction in order to use it properly. The smartphone applications typically had more intuitive and friendlier user interfaces. However, ample support documentation existed for the conventional system, whereas most of the applications had very little support. In many cases applications had no supporting documentation at all. While intuitiveness is most important for users to begin to learn a system, documentation is required to resolve complex problems.

Efficiency. The efficiency test revealed large differences between data collection times for each application. The results of the efficiency test can be seen in Table 9. Point collection times differed depending on the interface style of the applications. Applications that required many swipes, button pushes, and loading screens took longer for each point entry. Applications with efficiently designed interfaces took less time. While most applications were consistent in point collection times at all field locations, a few applications varied. The applications that varied in average collection time were those that were dependant on cellular data connection for uploading data, downloading a map cache, or retrieving form data. Data connection varied between sites, and was especially sporadic at periphery locations. Rural locations did not have any data connection, and as a result some applications that require a data connection to function did not initialize at all. At the Redwood Park site the smartphone's GNSS ceased functioning altogether. The only applications that could collect points at the Redwood Park site were those that allowed the user to use heads-up locating for manual placement.

The differences in point collection times revealed how significantly user interface design can affect time spent using an application.

Table 9. Application efficiency test averages for each location

Application	**Urban**			**Periphery**			**Rural**			**Average**
	Diridon Station	**Frank Ogawa**	**Oakland Library**	**Clyde Woolridge**	**Eden Canyon**	**Fairmont Ridge**	**Palomares**	**Redwood Park**	**Welch Creek**	
AnywhereGIS	7.5	10.2	9.9	13.5	9.0	8.0	6.9	-	9.6	9.3
Collector for ArcGIS	5.6	6.3	6.9	8.8	6.2	6.4	-	-	-	6.7
EpiCollect	9.3	11.9	10.3	11.2	9.3	10.9	8.0	-	9.6	10.1
GeoJot+	10.7	12.4	11.3	9.9	9.8	10.0	9.1	-	7.8	10.1
Geology Sample Collector	14.2	22.7	18	15.4	16.2	17.1	14.2	-	12.9	16.3
GeoODK Collect	18.9	19.2	19	18.6	14.8	17.4	19.5	-	16.9	18.0
Geopaparazzi	12.7	17.2	13.9	13.6	13.3	13.4	12.1	11.8	11.9	13.3
Map It – GPS Survey Collector	4.1	5.5	4.7	4.4	4.2	4.3	4.1	8	3.9	4.8
MapWithUs 3	12.7	16.3	14.9	28.8	12.7	13.5	-	-	-	16.5
MDC GIS	4.7	7.1	6.2	5.4	5.2	5.6	4.5	-	4.5	5.4
PointGIS	6.8	10.2	8.9	7.8	7.6	7.8	6.2	-	7.1	7.8
SuperSurv	8.3	9.7	8.8	9.2	8.8	9.2	8.4	-	8.3	8.8
TerraSync (Conventional)	5.0	6.7	5.0	5.0	5.0	5.1	5.0	-	4.9	5.2

The conventional system performed very efficiently during the efficiency test. Once the conventional system’s data collection form was started, data entry required an absolutely minimal number of user inputs. The conventional system was a product of much development and industry feedback, which clearly resulted in an efficient system.

Map It and MDC GIS were efficient collection smartphone applications, both similar to TerraSync in user interface design. The other smartphone applications required extraneous user inputs like updating location and swiping between form fields that could have been automated. Some applications did not clearly identify functions, provide user feedback, or relied on the network connection for immediate data processing which slowed time to entry completion. While the conventional system was not as initially intuitive as most of the smartphone applications, once learned it proved to be highly efficient.

Memorability. The memorability test showed that most applications allowed for adequate user retention. The results of the memorability test can be seen in Table 10. The time differences between an initial test, constructed identically to the learnability test, and the same test conducted one month later were recorded and classified into scores. A time difference of zero was considered optimal, as a zero time difference indicated perfect repeatability. Nearly all applications produced an improved time for each activity. Collector for ArcGIS scored particularly low in learnability due to its very complex and lengthy setup procedure. GeoJot+ also scored low on the memorability test due to its complex method of exporting data. PointGIS scored very well on the memorability test because of the overt simplicity of the application. However, the simplicity of PointGIS also limited its usability in other categories and narrowed its potential use cases. Overall, the combined scores showed that most applications performed reasonably well on the memorability test.

Table 10. Application memorability results

Application	Statistic	Setup	1st Point	Form	Export	Sum of Classes
AnywhereGIS	Time Difference	4:31	-0:07	0:08	2:19	13
	Score	2	4	5	2	
Collector for ArcGIS	Time Difference	10:00	-0:07	6:11	0:35	9
	Score	1	4	1	3	
EpiCollect	Time Difference	0:00	0:22	0:13	0:17	18
	Score	7	3	5	3	
GeoJot+	Time Difference	-0:04	0:32	2:52	8:07	11
	Score	6	2	2	1	
Geology Sample Collector	Time Difference	0:31	0:06	-0:06	2:30	16
	Score	4	5	6	1	
GeoODK Collect	Time Difference	0:04	0:01	5:37	0:07	16
	Score	6	7	1	2	
Geopaparazzi	Time Difference	0:00	0:40	4:04	0:04	16
	Score	7	1	2	6	
Map It – GPS Survey Collector	Time Difference	0:00	-0:01	1:13	0:39	20
	Score	7	7	3	3	
MapWithUs 3	Time Difference	-0:12	0:04	2:05	0:14	16
	Score	5	5	2	4	
MDC GIS	Time Difference	0:21	0:03	1:42	0:05	18
	Score	4	6	3	5	
PointGIS	Time Difference	0:00	0:07	0:00	0:06	23
	Score	7	4	7	5	
SuperSurv	Time Difference	0:12	0:40	-0:04	0:01	19
	Score	5	1	6	7	
TerraSync (Conventional)	Time Difference	10:00	0:04	0:07	0:04	18
	Score	1	5	6	6	

Error Rate. Instances of error were recorded for each application throughout all of the other usability tests. The results for the error test can be seen in Table 11. Simple errors were program anomalies, reported through user feedback or otherwise, that were encountered by the user. Fatal errors were any unexpected shutdown or compete loss of interaction by the application. Fatal errors were given doubled weight for the overall result seen in Table 11. Most of the smartphone applications experienced a fatal error at one time or another. Only GeoJot+, Map It, MDC GIS, and TerraSync did not experience any fatal errors, and these last three were incidentally the same applications that performed best on the efficiency test. The correlation between high efficiency and low error rate suggests either that simple interfaces reduce the probability of internal conflicts within a program, or better quality programming on the part of the developer accounted fro the improved efficiency and error reduction. The high number of errors held by many of the smartphone applications compared to the non-existence of errors in other applications and the conventional system indicates a significant disparity in programming quality in the smartphone marketplace.

Table 11. Application error test results

Application	**Simple Error**	**Fatal Error**	**Result**
AnywhereGIS	2	3	8
Collector for ArcGIS	0	2	4
EpiCollect	1	1	3
GeoJot+	0	0	0
Geology Sample Collector	2	1	4
GeoODK Collect	1	1	3
Geopaparazzi	0	2	4
Map It – GPS Survey Collector	0	0	0
MapWithUs 3	2	1	4
MDC GIS	0	0	0
PointGIS	0	1	2
SuperSurv	1	1	3
TerraSync (Conventional)	0	0	0

Satisfaction. A satisfaction test was conducted for each application. The results of the satisfaction questions can be found in Table 12. A result value was assigned for each application by summing the number of advantageous answers. The questions are arranged such that the first question is advantageously answered in the affirmative, and the second question in the negative, and so on repeating. Most applications performed tolerably. The most satisfactory applications included EpiCollect, GeoJot+, Map It, and MDC GIS, the last two being the same applications that had no errors and were found to be most efficient. Geology Sample Collector did not test well for satisfaction, as it suffered from an excessively complicated interface and very difficult data management requirements. User satisfaction is evidently related to the other conditions of usability.

Table 12. Application satisfaction test results

Application	**I'd Use Frequently**	**Unnecessarily Complex**	**Easy to Use**	**I Need Tech Support**	**Well Integrated**	**Inconsistent**	**Learn Quickly**	**Very Cumbersome**	**I Feel Confident**	**Need to Learn a Lot**	**Result**
AnywhereGIS	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	7
Collector ArcGIS	Yes	Yes	Yes	Yes	Yes	No	Yes	No	Yes	Yes	7
EpiCollect	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	10
GeoJot+	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	10
Geology Sample	No	Yes	No	No	No	Yes	No	Yes	No	Yes	1
GeoODK Collect	No	No	Yes	No	Yes	No	Yes	No	No	No	8
Geopaparazzi	No	No	Yes	Yes	No	Yes	Yes	No	Yes	Yes	5
Map It	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	10
MapWithUs 3	No	No	No	No	Yes	No	Yes	Yes	No	No	6
MDC GIS	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	10
PointGIS	No	No	Yes	No	Yes	No	Yes	No	No	No	8
SuperSurv	No	Yes	No	No	Yes	No	No	Yes	No	No	4
TerraSync	Yes	Yes	Yes	Yes	Yes	No	No	No	Yes	Yes	6

The conventional system, TerraSync, did not perform especially well in the satisfaction test. Smartphone applications had advantage over the conventional system because the convenience, intuitiveness, and appealing interface of smartphone applications offers greater potential to score satisfactorily. However, many of the drawbacks of the conventional system's satisfaction come from initial difficulty of use and time invested to learn, which are byproducts of its complicated but robust design. The robustness of the system's design is what prevents errors, establishes user confidence, and allows for complex data handling, which are attributes that many smartphone applications lack. Some of TerraSync's satisfaction issues are also assets in other respects.

Features. The features found in the applications were diverse. Features for each application were counted if present and noted in Table 13. The overall result in the table is the total count of features present. Some features were common throughout the applications, for instance camera support for attaching photographs, a GNSS accuracy display, customizable forms, and the ability to edit previously captured data. Other features were less commonly found, for instance viewing satellite constellation details, changing coordinate system reference frames, and saving basemap data to an internal cache. The applications with the most features, notably Collector for ArcGIS and SuperSurv, tended to be part of larger enterprise-level GIS software packages. The quality of similar features also varied. While some features were well-integrated parts of the applications, many features appeared to be poorly developed afterthoughts. Overall, features in collection applications were varied in inclusion, design, and quality.

Table 13. Application feature test results

Application	Camera	Attach Media	Accuracy Display	Coordinate Display	Altitude Display	Satellite Details	Heads-Up Capable	Set Coordinate System	Extra Sensor Support	Local Storage	Cloud Storage	Current Location Map	Review Map	Cache Map Data	Custom Data Overlays	Change Basemap	Custom Forms	Group Collaboration	Edit Previous	Free Data Export	Native GIS Output	Multiple Data Layers	Result
AnywhereGIS	x		x			x					x	x	x				x	x		x			9
Collector Arc	x		x	x			x	x		x	x	x	x		x	x	x	x	x	x	x	x	17
Epi Collect	x		x							x	x	x	x				x	x	x	x			10
GeoJot +	x		x	x	x				x	x	x		x			x	x	x	x		x		13
Geolo. Sample	x	x	x	x	x		x		x	x	x	x					x		x	x			13
Geo ODK	x		x	x	x					x	x		x		x	x	x	x	x	x			13
Geopaparazzi	x	x					x			x	x	x	x		x		x		x	x	x		12
Map It Mobile	x		x	x	x	x	x	x		x		x	x		x	x	x		x				14
MapWithUs	x	x	x				x			x	x	x	x	x	x	x	x		x		x		14
MDC GIS	x	x	x				x			x	x	x	x	x			x	x	x	x	x		14
Point GIS	x		x	x	x					x										x			6
Super Surv	x		x	x	x	x	x			x		x	x		x	x	x		x	x	x	x	16
Terra Sync	x		x	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x		x	x	19

TerraSync, the conventional system, supported the most features. Other initially non-present features could also be added on through the purchase of additional extensions. While none of the smartphone applications met or exceeded the feature offerings of the conventional system, several came close. Smartphones definitely have the flexibility to incorporate many, if not more features than the conventional system. Continued development will likely see more features added to smartphone applications.

Overall. Many of the smartphone applications scored well in the usability test. The overall results of the entire usability test can be seen in Table 14. Two applications exceeded the usability of the conventional system, while several came close. The experiment did not account for aspects of the application beyond usability. For instance one of the advantages of conventional high-end collection applications is the ability to manage data from multiple complex enterprise databases. However, for straightforward point data collection with reasonable amounts of attributes some smartphone applications appear to be more than adequate. However, notably more than half of the tested applications did not match the usability of the conventional system. No correlation was found between the usability of the applications and the user ratings or number of downloads seen in table 3. Therefore, it would be difficult for a user searching for a collection application to find one of quality without conducting his or her own usability test.

Table 14. Application usability test rank scores combined

Application	**Learnability**	**Efficiency**	**Memorability**	**Error Rate**	**Satisfaction**	**Features**	**Result Sum**
AnywhereGIS	5	5	2	1	5	2	20
Collector for ArcGIS	2	6	1	4	5	6	24
EpiCollect	7	4	4	5	7	2	29
GeoJot+	6	4	1	7	7	4	29
Geology Sample Collector	1	2	3	4	1	4	15
GeoODK Collect	4	1	3	5	6	4	23
Geopaparazzi	4	3	3	4	3	3	20
Map It – GPS Survey Collector	7	7	6	7	7	5	39
MapWithUs 3	3	2	3	4	4	5	21
MDC GIS	5	7	4	7	7	5	35
PointGIS	2	6	7	6	6	1	28
SuperSurv	1	5	5	5	2	6	24
TerraSync (Conventional)	1	7	4	7	4	7	30

During the application usability test an unanticipated complication was found. Despite using the same internal GNSS for positioning, accuracy and precision differed between certain applications. Some applications rounded decimal places of position coordinates, which, as predicted by Zandbergen (2009), caused point locations to arrange into a grid-like pattern leaving obvious gaps. Other applications required motion from the smartphones onboard accelerometer before updating location, meaning that progressive points were placed in exactly the same location unless the user moved about.

In peripheral areas where data service was sporadic some applications placed points many hundreds or thousands of meters in error, while other applications had no issues. The PointGIS application, even in urban areas, showed a tendency for consistently erroneously placing points tens of meters away from the test site, as seen in Figure 3.

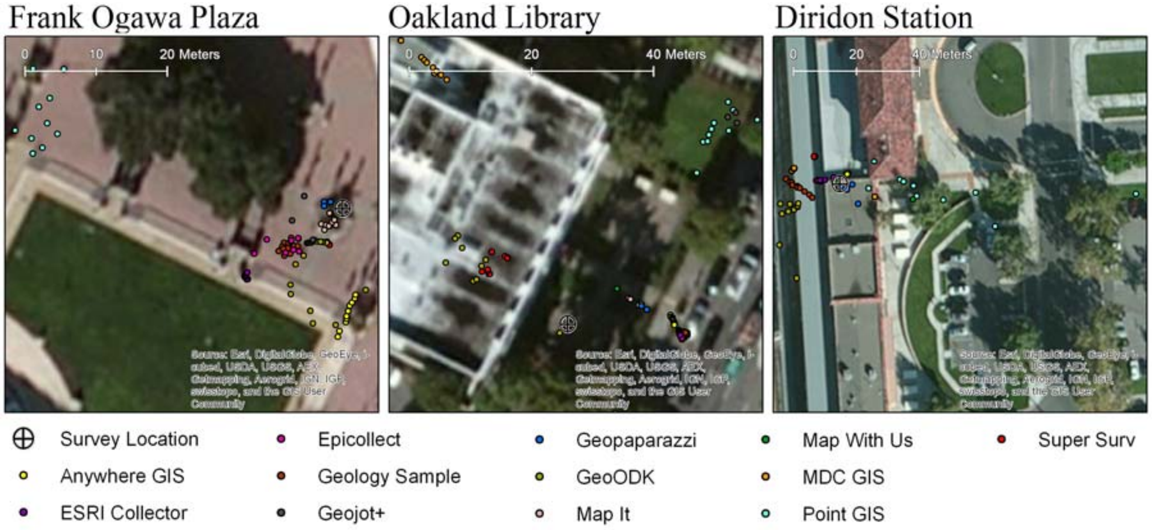


Figure 3. Display of smartphone application point distribution at three sites

Smartphone applications are likely programmed with different utilizations of a device's A-GPS location optimization features, some of which are ostensibly sensitive to data service availability and other conditions. The usability experiment was not designed to evaluate the accuracy properties of the applications themselves. An assumption was made that the same GNSS NMEA protocol feed would be interpreted the same by any application, but users should note that this is not the case. A further investigation into the properties of smartphone A-GPS and its relationship to data collection applications is advised.

Conclusion

Smartphone based MDCS have shortcomings compared to a conventional system, but they also have several advantages. Smartphone GNSS chipsets are inferior in both accuracy and precision to conventional systems. In addition, smartphone applications have wide quality variations that cannot be easily predicted. However, while observable, the differences between smartphone and conventional MDCS quality are not vast. Accuracy and usability of smartphones show continuing improvement over time. While conventional survey systems are necessary for the use case of complex database and centimeter level accuracy, a smartphone can easily fill the niche of a project consisting of a few layers and requiring accuracy to within about five meters. Most collection projects, therefore, are well served by the available capabilities of smartphone-based MDCS. The convenience of smartphone portability, multitasking, and inexpensiveness lends a great deal of credibility to the use of smartphones for collection work. Continued improvements in smartphone technology will further close the gap between smartphone and conventional systems.

The accuracy of smartphone GNSS chipsets show promise. Smartphone GNSS chipsets and tetherable chipsets are not as accurate as conventional survey grade GNSS; however only a few meters separates the accuracy between newer chipsets and survey-grade systems. Each successive generation of GNSS receiver chipset shows increasing technological sophistication and accuracy improvement toward the submeter. The portability of smartphone or tethered GNSS is also significant. Survey grade GNSS weigh several pounds and require cumbersome backpacks with external antennas to use in the field. Smartphones and tetherable GNSS weigh mere ounces and fit discretely into pockets. Trimble itself recently released a bluetooth tetherable survey-grade submeter accurate GNSS receiver for use with smartphones (GPS World Staff, 2015). Miniaturization of GNSS technology will soon allow for new accuracy levels for smartphones and tablets never before achieved.

Smartphone data collection applications lack complexity, but have potential. Many smartphone applications have agreeable interfaces and usable functions. However, some applications are not well developed and have significant usability problems. Furthermore, none of the tested applications offer the level of features and quality control found in conventional data collection software. Conventional data collection software is well developed and industry reviewed, with many years of operational experience and critique. While some smartphone applications proved to be very robust and usable, the freeform smartphone application market does not allow a user to easily curate the quality applications from the inferior. User reviews, ratings, number of downloads, and other provided discriminating information is not trustworthy for determining the usefulness of an application. Despite the promise shown by several applications, unless improved quality control methods are built into the smartphone application marketplace it will be difficult for users to locate the most worthwhile applications.

A number of further questions surfaced during the experiment. Anecdotal evidence suggested that GNSS receivers differed in location update rates, which means that positional accuracy between devices may differ in the context of continuous motion or sudden position change, both of which are frequent occurrences in field data collection. The GNSS test used all receivers while stationary around a fixed reference station. Furthermore, the CORS antennas, in order to get the best possible reading for tectonic surveys, were positioned in locations without any sky obstructions. Researchers agree that all GNSS receivers suffer in areas of heavy forest canopy obstruction, but the exact degree is not readily discernable without field-testing (Baker & Gaspard, 2007; Gakstatter, 2009; Wing & Eklund, 2007). The accuracy tests also showed that most consumer devices were very inaccurate during the first few seconds of collection, and then corrected themselves shortly thereafter. However, the methodology of the experiment was not designed to examine the time-to-fix characteristic. In order to investigate the effects of movement, obstructions, and time-to-fix on receivers a new experiment will have to be designed.

The proliferation of smartphones throughout our society has opened up a new paradigm in geographic field data collection. Average users now have access to powerful and portable computing devices with sophisticated position-finding capabilities. Applications are widely accessible and generally intuitive, allowing users to swiftly embark upon collection projects. While costly conventional collection systems remain dominant in terms of accuracy and product quality, smartphones and tablets show marked potential to reach conventional system capabilities. GNSS positioning accuracy continues to advance, and many application developers are cleverly improving the capabilities of collection applications. Mass crowdsourcing and digitizing of features on a global scale will enable remarkable feats of location finding. Geographic data will be accessible, useful, and life improving for all.

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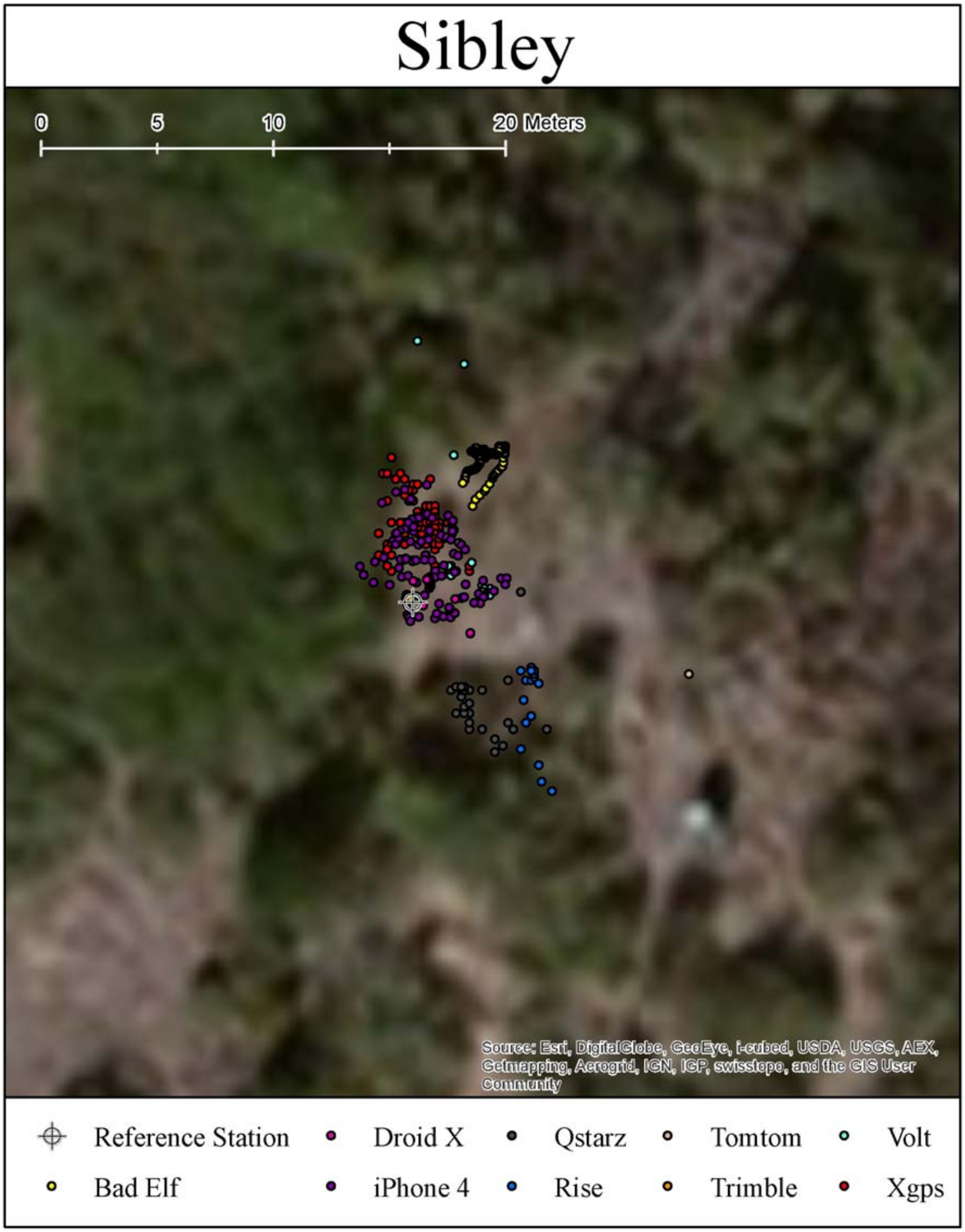
Appendix A: Supplemental Accuracy and Precision Experiment Figures



Source: Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

Figure 4. Data point distribution at the Sibley CORS site

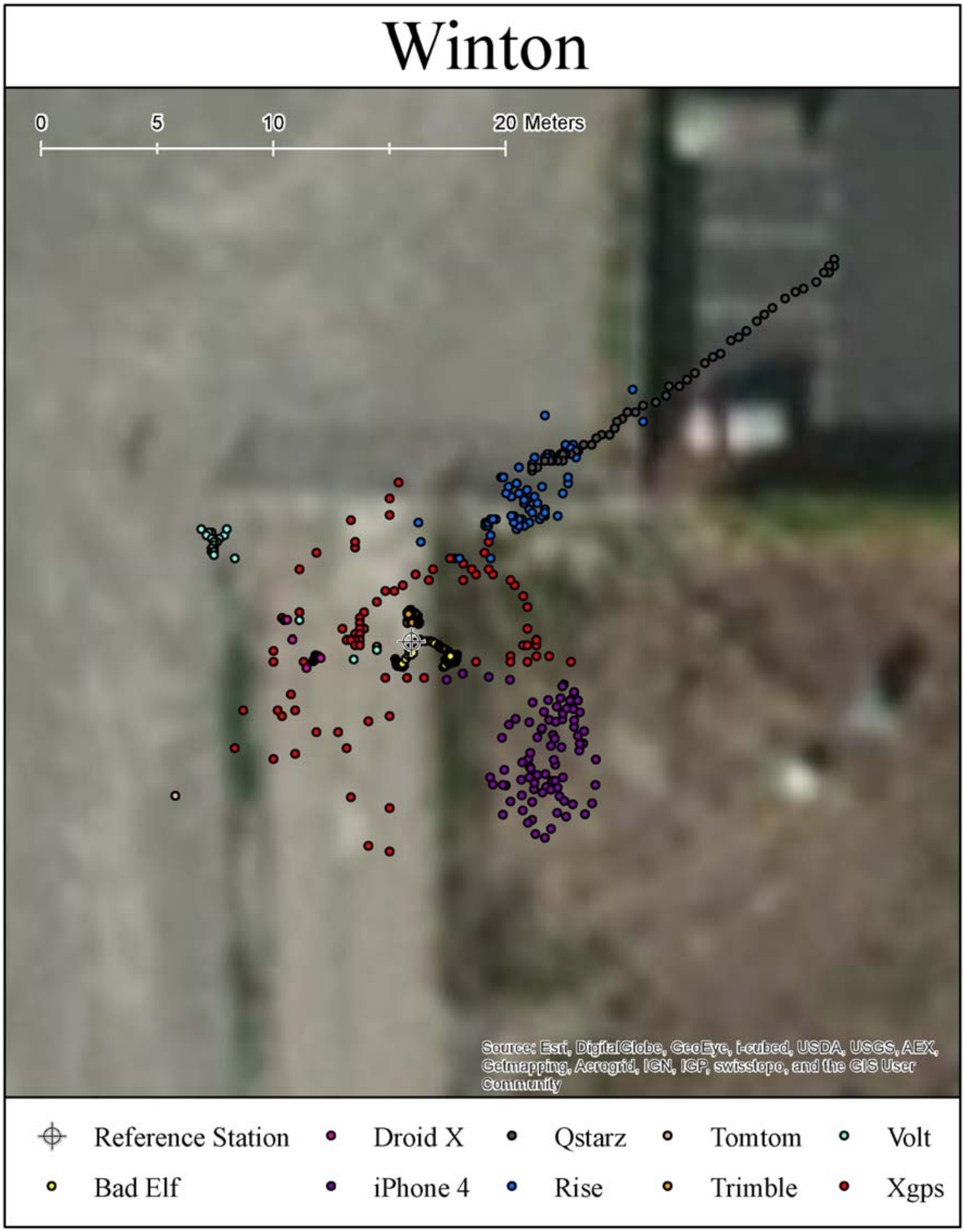


Figure 5. Data point distribution at the Winton CORS site

Source: Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

Figure 6. Data point distribution at the Cull Canyon CORS site

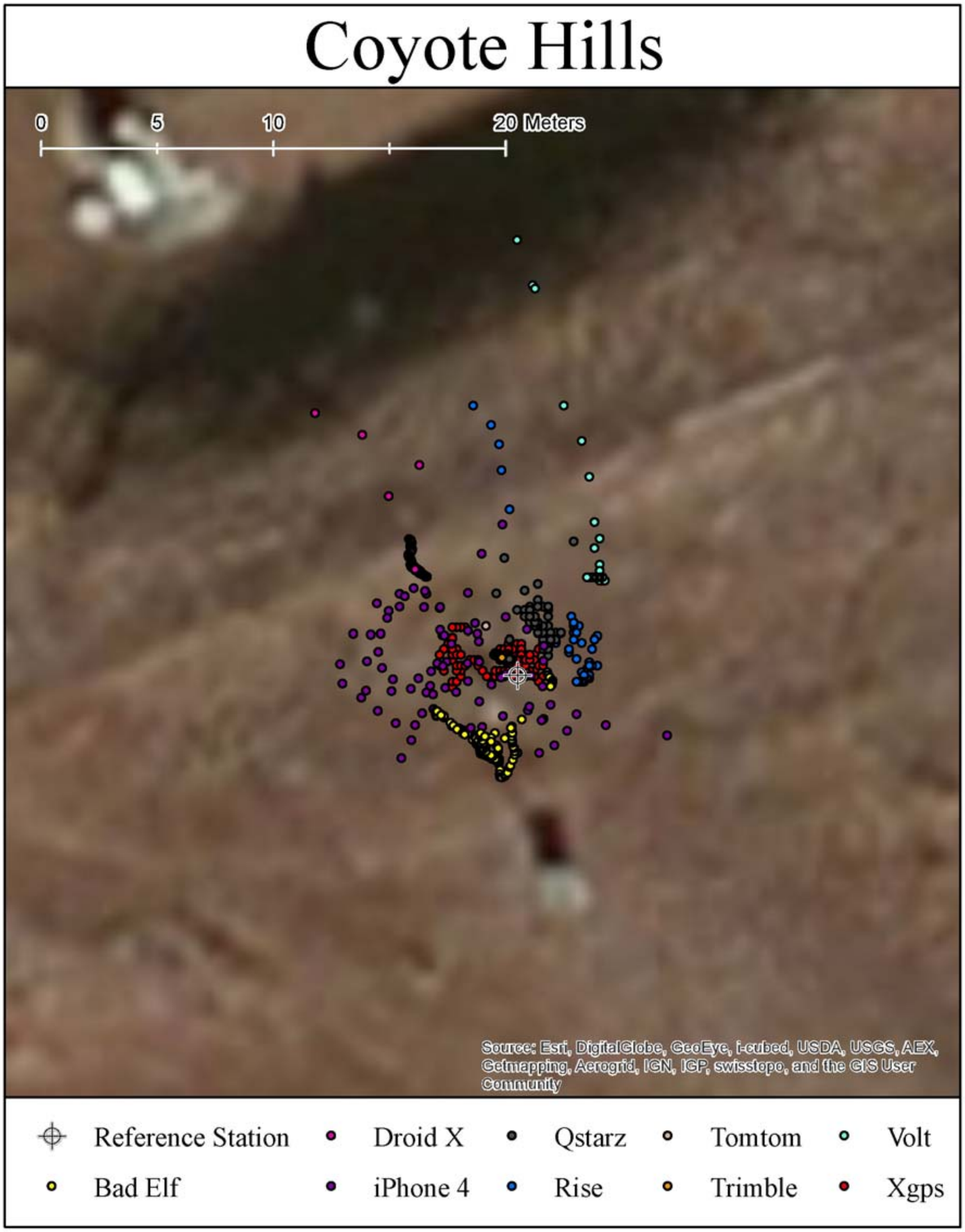
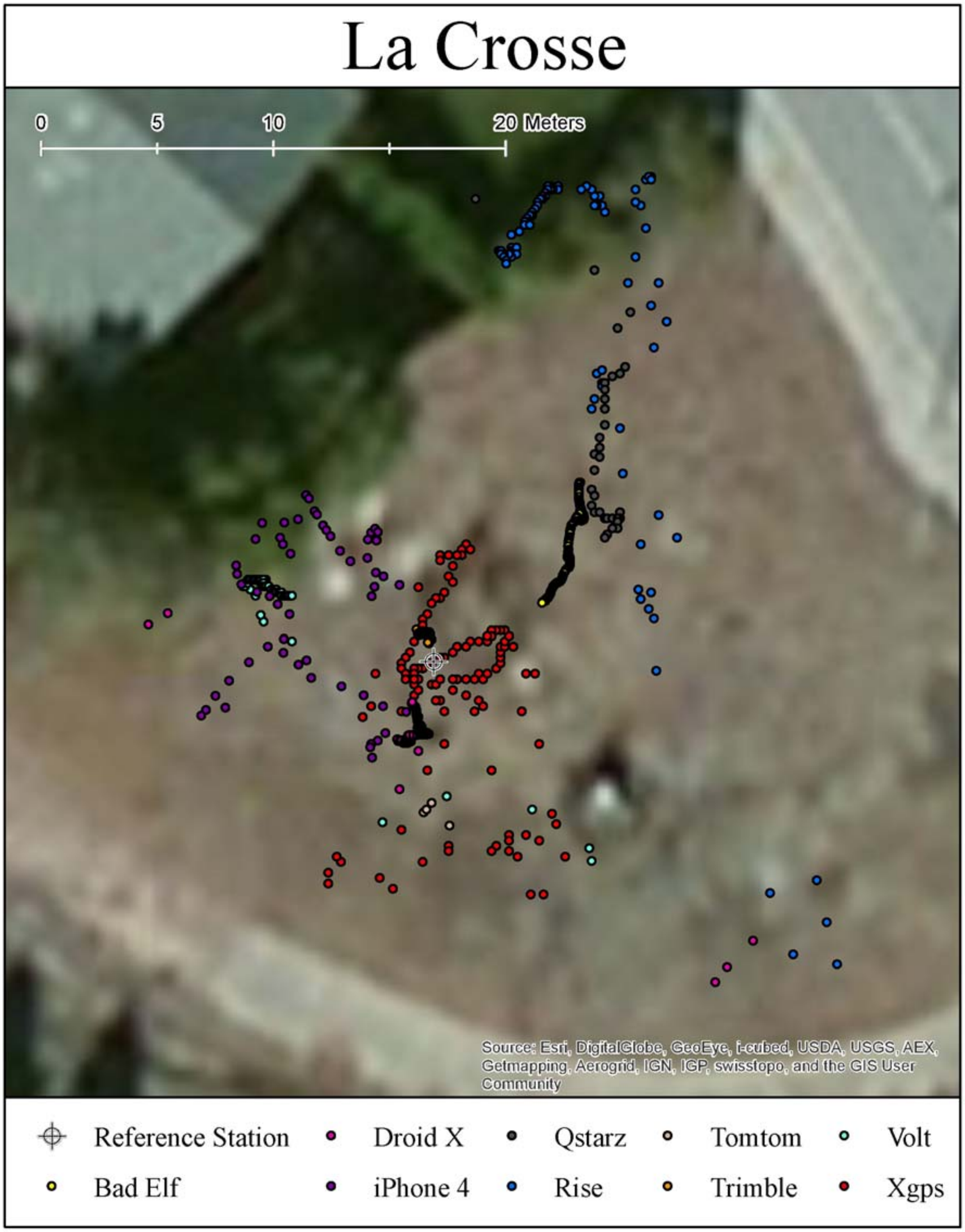


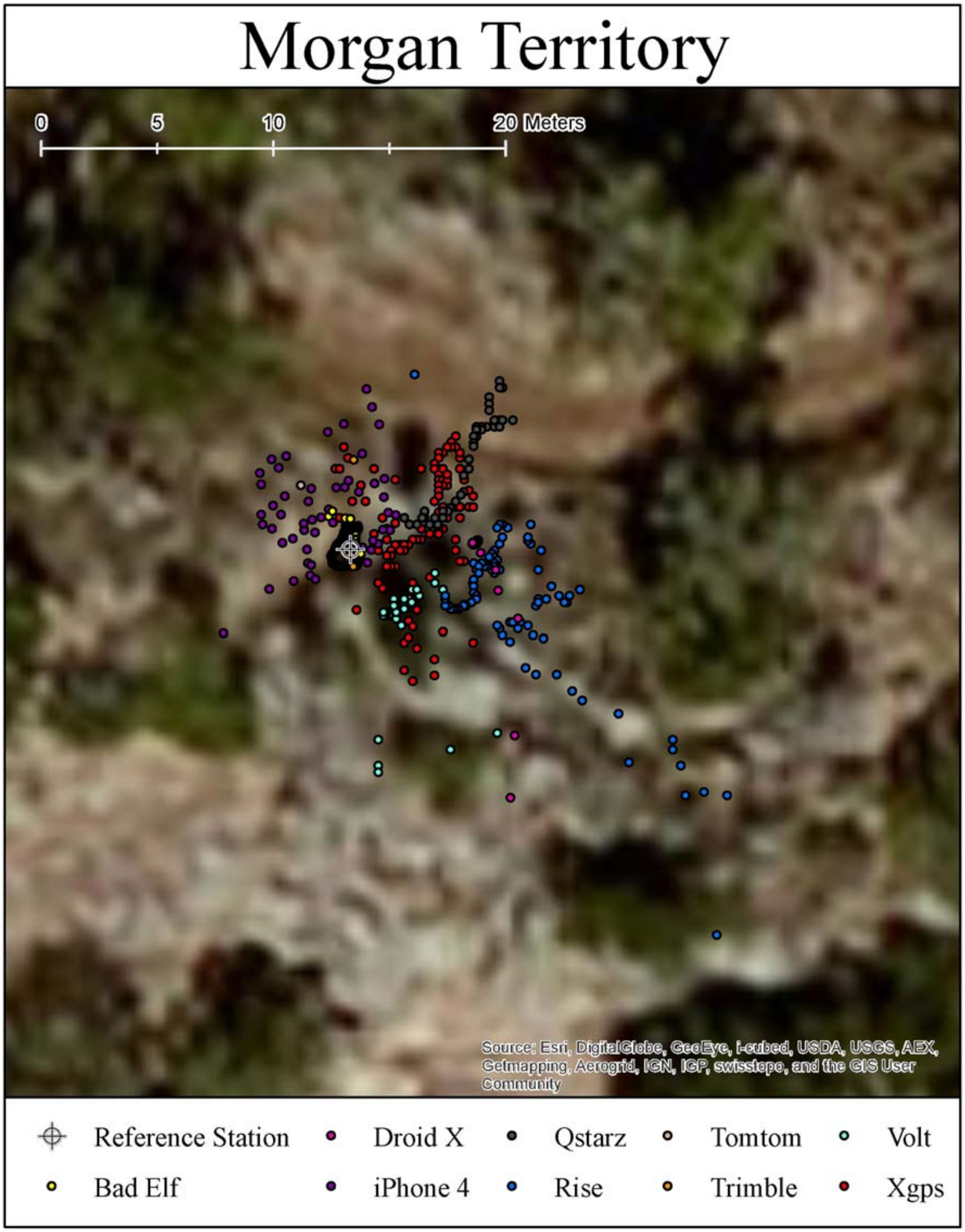
Figure 7. Data point distribution at the Coyote Hills CORS site

Figure 8. Data point distribution at the Mt. Hamilton CORS site



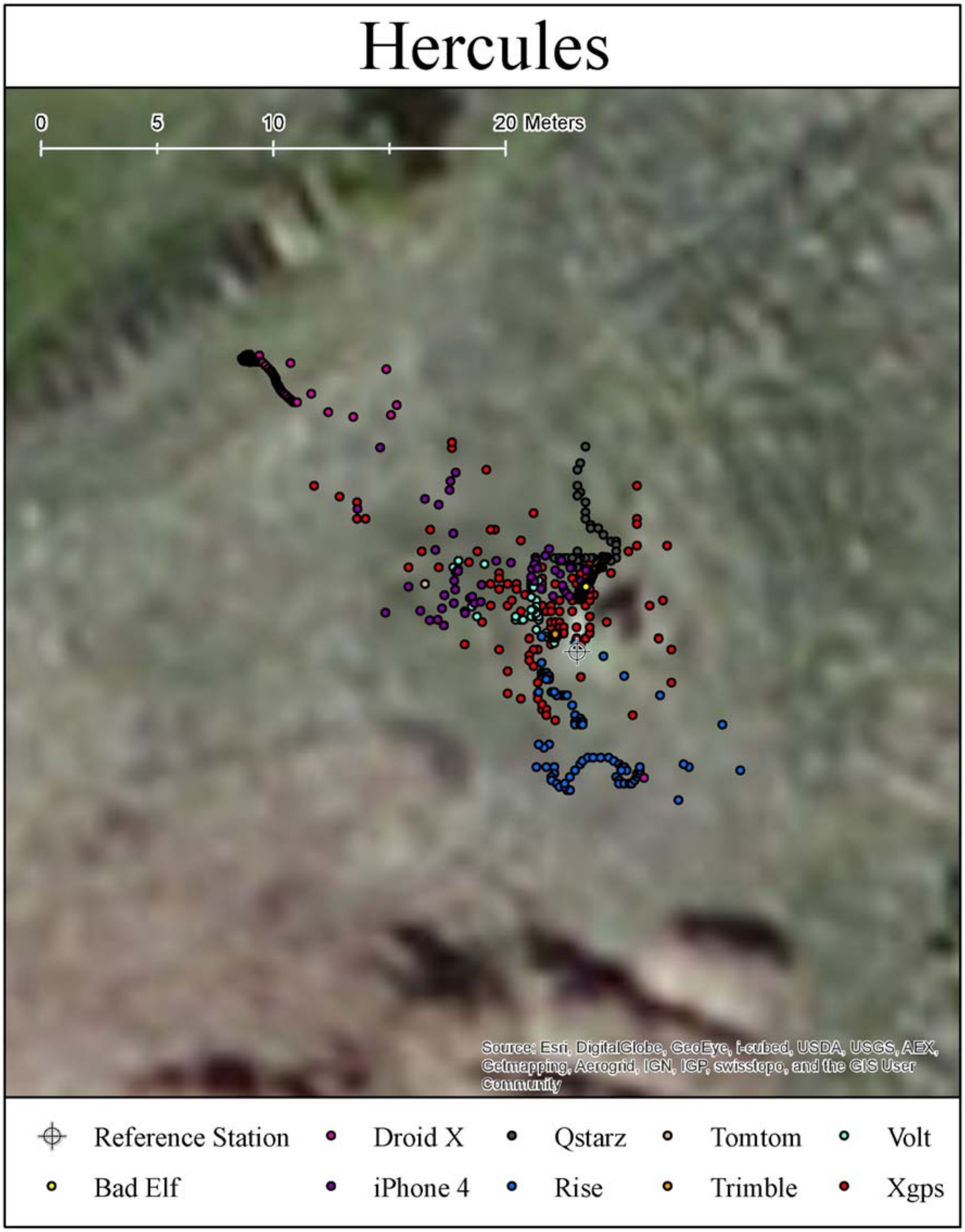
Source: Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

Figure 9. Data point distribution at the La Crosse CORS site



Source: Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

Figure 10. Data point distribution at the Morgan Territory CORS site



Source: Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

Figure 11. Data point distribution at the Hercules CORS site

Figure 12. Data point distribution at the Miller Knox CORS site

Appendix B: Supplemental Application Usability Experiment Tables

Table 15. Efficiency test results Ogawa Plaza

Network Download Speed: 14.62mbps
Network Upload Speed: 13.44mbps
Wi-Fi Detections: 19

Application	**Trial 1**	**Trial 2**	**Trial 3**	**Trial 4**	**Trial 5**	**Average**
	Trial 6	**Trial 7**	**Trial 8**	**Trial 9**	**Trial 10**	
AnywhereGIS	12	11	10	9	11	10.2
	9	10	11	10	9	
Collector for ArcGIS	10	6	6	6	6	6.3
	6	6	5	6	6	
EpiCollect	13	14	12	11	12	11.9
	11	11	13	11	11	
Geology Sample Collector	34	23	22	24	24	22.7
	19	18	20	21	22	
GeoJot+	15	13	11	14	12	12.4
	13	13	11	11	11	
GeoODK Collect	19	19	20	17	20	19.2
	16	19	20	21	21	
Geopaparazzi	20	16	18	18	16	17.2
	16	17	17	17	17	
Map It – GPS Survey Collector	8	6	5	5	5	5.5
	5	5	5	6	5	
MapWithUs 3	18	15	16	17	16	16.3
	14	16	17	17	17	
MDC GIS	10	8	8	6	7	7.1
	6	6	6	7	7	
PointGIS	13	9	10	10	12	10.2
	9	10	10	10	9	
SuperSurv	9	10	10	10	10	9.7
	10	10	9	9	10	
TerraSync (Conventional)	8	7	7	7	7	6.7
	6	6	6	7	6	

Table 16. Efficiency test results Oakland Library

Network Download Speed: 14.45mbps
Network Upload Speed: 4.31mbps
Wi-Fi Detections: 6

Application	**Trial 1**	**Trial 2**	**Trial 3**	**Trial 4**	**Trial 5**	**Average**
	Trial 6	**Trial 7**	**Trial 8**	**Trial 9**	**Trial 10**	
AnywhereGIS	12	10	10	9	8	9.9
	11	10	10	10	9	
Collector for ArcGIS	8	7	6	7	8	6.9
	7	7	6	6	7	
EpiCollect	13	11	10	12	9	10.3
	10	10	9	10	9	
Geology Sample Collector	22	16	18	17	21	18.0
	17	19	17	16	17	
GeoJot+	13	12	12	10	13	11.3
	11	10	10	12	10	
GeoODK Collect	20	19	17	16	19	19.0
	19	20	22	19	19	
Geopaparazzi	13	14	13	12	12	13.9
	13	13	14	20	15	
Map It – GPS Survey Collector	5	5	5	5	5	4.7
	4	5	4	4	5	
MapWithUs 3	13	13	15	15	13	14.9
	16	16	18	16	14	
MDC GIS	6	7	6	6	6	6.2
	6	6	6	6	7	
PointGIS	11	8	8	9	9	8.9
	10	9	9	8	8	
SuperSurv	10	9	8	9	9	8.8
	8	8	9	9	9	
TerraSync (Conventional)	5	5	5	5	5	5.0
	6	5	4	5	5	

Table 17. Efficiency test results Diridon Station

Network Download Speed: 9.27mbps *Network Upload Speed: 5.27mbps* *Wi-Fi Detections: 6*						
Application	**Trial 1**	**Trial 2**	**Trial 3**	**Trial 4**	**Trial 5**	**Average**
	Trial 6	**Trial 7**	**Trial 8**	**Trial 9**	**Trial 10**	
AnywhereGIS	10	7	7	8	7	7.5
	7	7	8	7	7	
Collector for ArcGIS	6	6	6	5	6	5.6
	5	7	5	5	5	
EpiCollect	13	10	10	8	9	9.3
	8	8	8	11	8	
Geology Sample Collector	16	14	15	14	14	14.2
	13	13	13	14	16	
GeoJot+	12	11	10	10	11	10.7
	11	11	11	10	10	
GeoODK Collect	19	18	19	19	18	18.9
	19	19	17	21	20	
Geopaparazzi	11	15	15	14	12	12.7
	12	11	12	12	13	
Map It – GPS Survey Collector	4	4	4	4	4	4.1
	4	4	4	5	4	
MapWithUs 3	13	12	12	14	12	12.7
	12	13	13	14	12	
MDC GIS	5	5	5	5	6	4.7
	4	5	4	4	4	
PointGIS	7	7	6	7	8	6.8
	7	7	6	6	7	
SuperSurv	9	8	8	9	8	8.3
	8	8	9	8	8	
TerraSync (Conventional)	5	5	5	5	5	5.0
	5	5	5	5	5	

Table 18. Efficiency test results Clyde Woolridge

Network Download Speed: 1.84mbps
Network Upload Speed: 0.15mbps
Wi-Fi Detections: 0

Application	**Trial 1**	**Trial 2**	**Trial 3**	**Trial 4**	**Trial 5**	**Average**
	Trial 6	**Trial 7**	**Trial 8**	**Trial 9**	**Trial 10**	
AnywhereGIS	13	12	14	11	13	13.5
	12	16	12	16	16	
Collector for ArcGIS	9	9	11	9	10	8.8
	8	8	8	8	8	
EpiCollect	11	10	12	10	11	11.2
	12	11	12	11	12	
Geology Sample Collector	19	14	15	14	15	15.4
	15	15	15	16	16	
GeoJot+	11	8	10	9	10	9.9
	10	10	10	11	10	
GeoODK Collect	17	17	20	19	17	18.6
	18	19	20	21	18	
Geopaparazzi	14	14	14	13	13	13.6
	13	15	13	14	13	
Map It – GPS Survey Collector	5	4	4	5	4	4.4
	5	4	5	4	4	
MapWithUs 3	16	51	43	14	14	28.8
	70	19	23	23	15	
MDC GIS	5	5	6	7	5	5.4
	5	4	5	6	6	
PointGIS	8	8	8	9	7	7.8
	8	7	8	7	8	
SuperSurv	9	10	9	9	9	9.2
	9	9	9	10	9	
TerraSync (Conventional)	5	6	5	5	5	5.0
	5	5	4	5	5	

Table 19. Efficiency test results Fairmont Ridge

Network Download Speed: 6.38mbps
Network Upload Speed: 1.25mbps
Wi-Fi Detections: 0

Application	**Trial 1**	**Trial 2**	**Trial 3**	**Trial 4**	**Trial 5**	**Average**
	Trial 6	**Trial 7**	**Trial 8**	**Trial 9**	**Trial 10**	
AnywhereGIS	8	9	9	7	8	8.0
	8	8	9	7	7	
Collector for ArcGIS	6	6	6	6	7	6.4
	6	7	7	6	7	
EpiCollect	10	11	10	9	10	10.9
	12	12	10	10	15	
Geology Sample Collector	17	19	17	18	17	17.1
	16	15	18	18	16	
GeoJot+	9	10	8	9	10	10.0
	11	10	11	12	10	
GeoODK Collect	18	17	16	17	15	17.4
	20	18	18	17	18	
Geopaparazzi	12	14	14	14	13	13.4
	13	14	13	12	15	
Map It – GPS Survey Collector	5	4	4	5	4	4.3
	4	4	4	5	4	
MapWithUs 3	13	14	13	12	15	13.5
	13	13	15	13	14	
MDC GIS	6	6	5	5	5	5.6
	6	6	6	6	5	
PointGIS	9	7	10	7	7	7.8
	7	8	8	7	8	
SuperSurv	10	9	9	9	10	9.2
	10	9	9	8	9	
TerraSync (Conventional)	5	5	5	5	5	5.1
	5	6	5	5	5	

Table 20. Efficiency test results Eden Canyon

Network Download Speed: 6.59mbps *Network Upload Speed: 3.46mbps* *Wi-Fi Detections: 0*						
Application	**Trial 1**	**Trial 2**	**Trial 3**	**Trial 4**	**Trial 5**	**Average**
	Trial 6	**Trial 7**	**Trial 8**	**Trial 9**	**Trial 10**	
AnywhereGIS	11	10	9	9	8	9.0
	9	7	8	9	10	
Collector for ArcGIS	7	6	6	6	5	6.2
	6	7	6	6	7	
EpiCollect	10	10	9	8	11	9.3
	8	9	9	9	10	
Geology Sample Collector	17	16	16	18	15	16.2
	14	17	16	16	17	
GeoJot+	10	11	10	9	9	9.8
	10	10	10	9	10	
GeoODK Collect	15	14	14	13	16	14.8
	15	16	15	16	14	
Geopaparazzi	11	15	15	13	12	13.3
	14	13	13	14	13	
Map It – GPS Survey Collector	4	4	4	4	4	4.2
	6	4	4	4	4	
MapWithUs 3	12	12	13	13	12	12.7
	12	13	15	13	12	
MDC GIS	5	5	5	6	6	5.2
	5	5	5	5	5	
PointGIS	7	8	8	9	7	7.6
	8	7	7	7	8	
SuperSurv	9	10	9	8	8	8.8
	9	9	8	9	9	
TerraSync (Conventional)	5	5	5	5	5	5.0
	5	6	6	4	4	

Table 21. Efficiency test results Redwood Park

Network Download Speed: no signal
Network Upload Speed: no signal
Wi-Fi Detections: 0

Application	**Trial 1**	**Trial 2**	**Trial 3**	**Trial 4**	**Trial 5**	**Average**
	Trial 6	**Trial 7**	**Trial 8**	**Trial 9**	**Trial 10**	
AnywhereGIS	-	-	-	-	-	-
	-	-	-	-	-	
Collector for ArcGIS	-	-	-	-	-	-
	-	-	-	-	-	
EpiCollect	-	-	-	-	-	-
	-	-	-	-	-	
Geology Sample Collector	-	-	-	-	-	-
	-	-	-	-	-	
GeoJot+	-	-	-	-	-	-
	-	-	-	-	-	
GeoODK Collect	-	-	-	-	-	-
	-	-	-	-	-	
Geopaparazzi	12	11	12	11	12	11.8
	12	12	12	12	12	
Map It – GPS Survey Collector	10	10	9	8	6	8.0
	8	8	7	6	8	
MapWithUs 3	-	-	-	-	-	-
	-	-	-	-	-	
MDC GIS	-	-	-	-	-	-
	-	-	-	-	-	
PointGIS	-	-	-	-	-	-
	-	-	-	-	-	
SuperSurv	-	-	-	-	-	-
	-	-	-	-	-	
TerraSync (Conventional)	-	-	-	-	-	-
	-	-	-	-	-	

Table 22. Efficiency test results Fish Ranch

Network Download Speed: no signal
Network Upload Speed: no signal
Wi-Fi Detections: 0

Application	**Trial 1**	**Trial 2**	**Trial 3**	**Trial 4**	**Trial 5**	**Average**
	Trial 6	**Trial 7**	**Trial 8**	**Trial 9**	**Trial 10**	
AnywhereGIS	18	10	9	10	8	9.6
	8	8	8	9	8	
Collector for ArcGIS	-	-	-	-	-	-
	-	-	-	-	-	
EpiCollect	10	10	9	9	10	9.6
	11	9	9	9	10	
Geology Sample Collector	17	12	12	12	12	12.9
	13	12	12	13	14	
GeoJot+	8	7	8	8	7	7.8
	8	8	8	8	8	
GeoODK Collect	17	19	19	18	16	16.9
	15	16	15	17	17	
Geopaparazzi	12	11	12	13	12	11.9
	12	12	12	11	12	
Map It – GPS Survey Collector	4	4	4	3	4	3.9
	4	4	4	4	4	
MapWithUs 3	-	-	-	-	-	-
	-	-	-	-	-	
MDC GIS	4	5	4	5	4	4.5
	4	5	5	4	5	
PointGIS	6	7	7	7	7	7.1
	8	8	6	7	8	
SuperSurv	9	8	8	10	8	8.3
	8	8	8	8	8	
TerraSync (Conventional)	5	5	5	5	5	4.9
	5	5	5	5	4	

Table 23. Efficiency test results Palomares Canyon

Network Download Speed: no signal
Network Upload Speed: no signal
Wi-Fi Detections: 0

Application	**Trial 1**	**Trial 2**	**Trial 3**	**Trial 4**	**Trial 5**	**Average**
	Trial 6	**Trial 7**	**Trial 8**	**Trial 9**	**Trial 10**	
AnywhereGIS	9	7	7	7	6	6.9
	6	8	6	7	6	
Collector for ArcGIS	-	-	-	-	-	-
	-	-	-	-	-	
EpiCollect	12	7	8	8	7	8.0
	7	8	8	7	8	
Geology Sample Collector	17	14	14	15	13	14.2
	16	13	13	12	15	
GeoJot+	11	10	8	8	9	9.1
	9	9	8	9	10	
GeoODK Collect	20	19	22	18	18	19.5
	20	19	18	22	19	
Geopaparazzi	11	11	12	13	14	12.1
	13	12	11	12	12	
Map It – GPS Survey Collector	5	4	4	4	4	4.1
	4	4	4	4	4	
MapWithUs 3	-	-	-	-	-	-
	-	-	-	-	-	
MDC GIS	5	5	5	5	4	4.5
	4	4	5	4	4	
PointGIS	6	6	7	7	6	6.2
	6	6	6	6	6	
SuperSurv	9	8	9	8	9	8.4
	9	8	8	8	8	
TerraSync (Conventional)	5	5	5	5	5	5.0
	5	5	5	5	5	