USER PERFORMANCE AND EXPERIENCE WITH VARYING GPS ACCURACY FOR LOCATION FINDING IN AGRICULTURAL FIELD RESEARCH

A Thesis Submitted to the
College of Graduate and Postdoctoral Studies
in Partial Fulfilment of the Requirements
for the Degree of Master of Science
in the Department of Computer Science
University of Saskatchewan
Saskatoon

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ABSTRACT

Accurate location information in a mobile map application is imperative within specialized domains like agricultural field research where users often carry out location-finding tasks. This is particularly relevant in agricultural research where field plots are small and similar in visual appearance. Location inaccuracy can result in difficulties determining the exact location of a target plot, leading to increased time and manual effort for plot identification. While smartphone map applications are widely used for wayfinding, GPS accuracy may not be sufficient for location-finding tasks in agricultural contexts, especially when the error in location accuracy equals or exceeds the size of the target plot. There is little known about smartphone GPS reliability and user experience during these tasks, and how inaccuracy affects user performance and trust in location information for agricultural field research tasks. This thesis investigates the effects of GPS accuracy on the usability of a map application for finding locations in agricultural field research. Two empirical studies were conducted to evaluate smartphone GPS accuracy and the influence of error rates on user performance and trust in the system while performing location-finding tasks in an agricultural field research scenario. The results from these studies establish a direct correlation between high error rates and diminished performance, resulting in reduced trust in the provided location information. Additionally, the results highlight various strategies employed to mitigate the reduced accuracy. This new knowledge can improve user experience in location-based applications through the implementation of best practices to provide better user support.

ACKNOWLEDGEMENTS

I would like to thank my supervisor, Carl Gutwin, for his guidance and input during my study program. I would also like to thank my thesis committee for their valuable comments and suggestions.

Thank you to my family for their unwavering support and encouragement. Thank you to my dear people, who always have my best interests at heart.

For my parents and my brother

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LIST OF ABBREVIATIONS

ANOVA	Analysis of Variance
ART	Aligned Rank Transform
DGPS	Differential Global Positioning System
DOP	Dilution of Precision
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HARS	High Accuracy and Robustness Service
HCI	Human-Computer Interaction
HRTD	High Resolution Topographic Data
IoT	Internet of Things
JSON	JavaScript Object Notation
MOOC	Massive Open Online Course
NRTK	Network Real-Time Kinematic
PPK	Post-Processing Kinematic
PPP	Precise Point Positioning
PPS	Precise Positioning Service
PNT	Positioning, Navigation and Timing
RTK	Real-Time Kinematic
RM-ANOVA	Repeated Measures Analysis of Variance

SA	Selective Availability
SBAS	Satellite-Based Augmentation Systems
SDK	Software Development Kit
SPS	Standard Positioning Service
TLX	Task Load Index
TTFF	Time To First Fix
Wi-Fi	Wireless Fidelity

CHAPTER 1

INTRODUCTION

Mobile map applications are frequently used by people to help them find locations in the real world. People also use these apps to locate themselves and navigate unfamiliar environments. These map apps typically display a full-screen map view of the user’s current environment on app startup, along with various options to interact with the map as well as the app interface. One of the options is the ability to choose from among the various map representations, such as top-down view [97], Street View [98], and 3D view [99], to start using the map in that mode. By default, most map apps show a top-down map view of the surroundings, with the user's current location indicated by a visual marker that is sometimes referred to as a location pin, location marker, or location dot if it is represented by a circle, as in Google Maps [100] and Apple Maps [101].

Figure 1.1 shows examples of the most widely used mobile map applications with a top-down map view and the user's current location indicated on the map with a blue marker. The work presented in this thesis focuses on the top-down map view, which is the most often used map representation and is employed in both of the custom map apps created for the two research studies covered in this thesis.

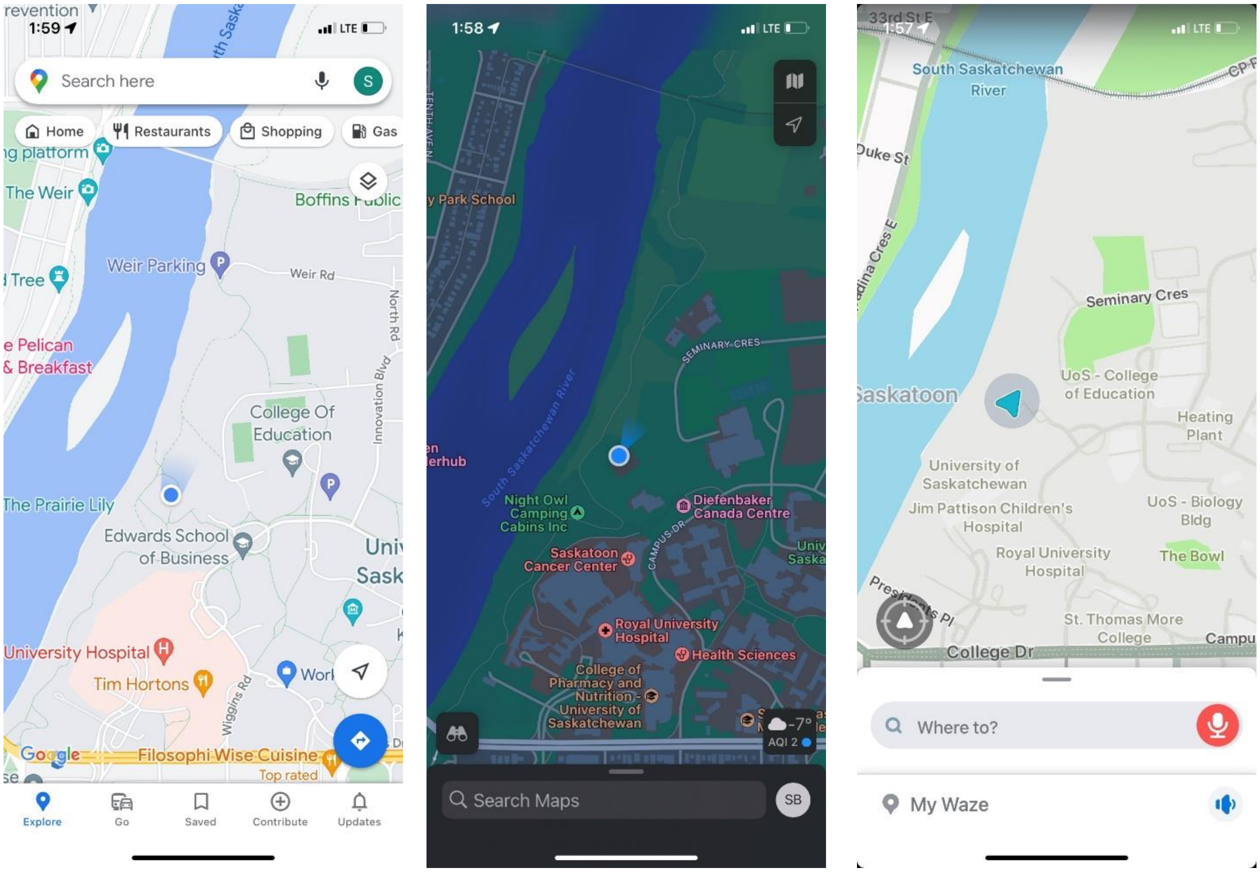


Figure 1.1: Top-down map view in (left) Google Maps [100], (middle) Apple Maps [101], (right) Waze [102]. User's current location is shown with a blue dot in Google Maps and Apple Maps, and with a blue triangle in Waze.

Location services and sensors available on smartphones use a combination of GPS, Wi-Fi, and cell towers to determine a user's current location and provide the most accurate location possible. GPS is considered to be the most accurate source of location information when the device is able to receive a strong signal through the GPS sensors [88]. It serves as a primary source of location information as it is available on virtually all smartphones and can obtain a device's location without the need for network connectivity [82]. However, when GPS signal transmission to the receiving devices is disrupted, other location services (Wi-Fi access points and cell-tower triangulation) are used to get a location fix [22,103]. These other services are less accurate than GPS, and often have larger error margins but are used to determine location when GPS signals are weak or unavailable.

GPS is a reliable source of navigation; however, its accuracy can be degraded by many factors, including signal obstruction by buildings, trees, or other objects; mapping errors; disabled device settings; and poor weather [104]. Therefore, for any location-finding task that the user attempts, there is a question about whether the location sensed by the device is accurate enough. Fundamentally, these tasks involve matching the information on the screen (i.e., the map and the location dot) with the visual information in the real world around the user. In many of these tasks, the device's location is accurate enough because the amount of error is less than the size of the target (e.g., a building). Additionally, there are landmarks that are visible in both the map and the real world that allow the user to match up the information on the screen with the real world in front of them. The popularity and success of mobile map applications demonstrate that users are able to successfully complete location-finding tasks in many situations. However, there are some scenarios where location-finding can be more challenging. One such scenario involves finding test plots in an agricultural field. These are small rectangular areas, typically 2-6 metres long and 1-2 metres wide, that contain a particular crop variety or treatment. Each plot in the field is a uniquely identifiable location datapoint in the array of rows and columns of plots, where many plots are spaced very closely together in the layout. Therefore, the location accuracy is required to be sufficient to correctly identify a particular plot. Figure 1.2 shows one such agricultural field with test plots in the layout as described above (which all look indistinguishable because of the same or homogenous crop varieties).

Figure 1.2: An overview image of an agricultural field with six columns of same-size plots.

Agricultural field researchers who regularly visit these test plots can benefit from a mobile application that could help them find specific plots. For example, a researcher may wish to visit the plots of specific wheat varieties to check their current status. However, for the mobile app to be useful, it is important that the location accuracy of the mobile map application is sufficient, as the researcher needs to be able to accurately identify the plots they are interested in.

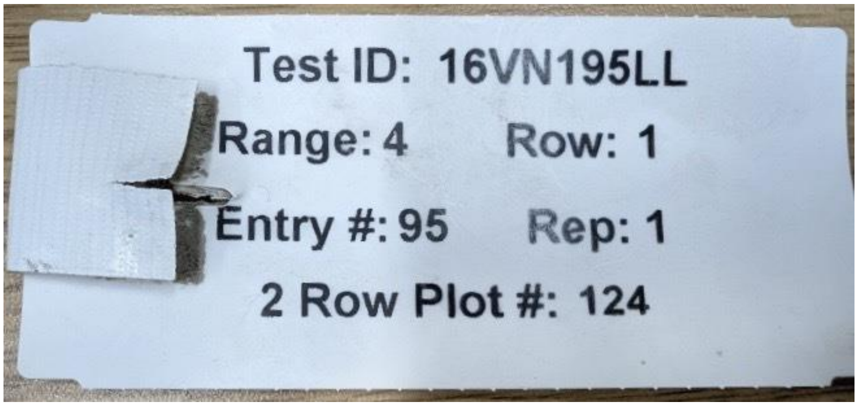
The agricultural test plots scenario presents two challenges that make the location-finding task more difficult. First, the location targets are smaller than in other types of tasks. For example, the front of the plot is usually the shorter edge, about 1-2 metres wide. Second, there are often few landmarks that can be used to match up the map information to the real world, since many test plots look similar and there are few external objects, such as signposts and markers, in the field.

Location-finding tasks, common and regularly carried out by agricultural field researchers, involve various methods to identify specific plots in the field. These methods include in-field location markers like flags and plot tags, the use of nearby landmarks such as trees, reliance on field notes containing plot location information, using measuring tapes to determine distances between landmarks and target plots, and the use of dedicated GPS receivers with extensive setup [8].

While these methods assist in plot identification, there are situations where they become impractical or demand excessive effort. For example, Figure 1.3 displays a plot tag with relevant plot information typically placed at plots' corners. Locating a specific plot using these tags requires visiting each tag placed at the plot corners to find the target plot. Moreover, these in-field markers might be temporary or relocated due to activities like harvesting. Landmarks may not consistently exist near the plots of interest; field notes may lack uniform interpretation; tape measures require additional effort to locate plots because of measuring distance from a landmark that may not exist in proximate distance to the target plot; and researchers may lack access to highly accurate GPS receivers.

In contrast, smartphones are advanced and easily accessible tools equipped with GPS technology. Their portability can significantly aid location-finding tasks in the field. Understanding the accuracy level achieved by smartphones becomes crucial in evaluating whether mobile GPS is sufficiently accurate for location-finding tasks and in assessing the impact of reduced accuracy on task performance.

The two studies presented in this thesis contribute novel findings regarding smartphone location accuracy and the effects of reduced location accuracy on users’ behaviour and their ability to perform location-finding tasks in an agricultural field research scenario.



Test ID: 16VN195LL

Range: 4 Row: 1

Entry #: 95 Rep: 1

2 Row Plot #: 124

Figure 1.3: A plot tag with information about one of the field plots depicted in Figure 1.2.

1.1 PROBLEM AND MOTIVATION

There is a paucity of research on the location accuracy of mobile map applications for agricultural field research tasks and the impact of reduced accuracy on users. Mobile GPS is accurate enough for wayfinding to larger landmarks like buildings or parks, which are readily visible and distinguishable from a distance. However, the location accuracy is insufficient for location-finding tasks in agricultural fields, where test plots are smaller and closely spaced. GPS is normally accurate to within 4.9 metres under ideal conditions [25], but this is not enough to accurately identify test plots with as little as 0.5 metres of gap between them. This thesis investigates the effects of GPS accuracy on the usability of an app for finding locations in agricultural field research.

1.2 SOLUTION

To investigate how location accuracy affects usability of apps for agricultural field research, the following research questions needed to be answered:

- RQ1: Do different network and location settings of a smartphone affect the accuracy and precision of the location data received?
- RQ2: Which device settings are ideal for receiving the most accurate and precise location data?
- RQ3: What is the effect of reduced location accuracy on the user task of location finding?
- RQ4: What is the user experience of different levels of location accuracy?
- RQ5: What strategies do users employ to navigate situations of insufficient location accuracy?

To address these questions, two research studies were designed and conducted on Android smartphones. Study 1 addressed RQ1 and RQ2, considering various aspects of location such as accuracy, precision, error, and the factors that affect them. Location data was collected under different device settings to assess the quality of the location information. The effect of sky cover conditions on location accuracy and precision was also analysed.

Study 2 was designed to gather data and insights related to the location accuracy required for location-finding tasks carried out in agricultural field research. The study required participants to perform the tasks in an agricultural test field setup under various accuracy levels, addressing RQ3-RQ5. The participants were asked questions about their use of and trust in the location information while completing the tasks, and the various strategies they employed in case of GPS inaccuracy. The results of the study yielded valuable insights into the user experience of performing location-finding tasks at different levels of GPS accuracy and the strategies they employed when faced with inaccurate location information.

1.3 STEPS TO THE SOLUTION

The solution involved two parts. The first part addressed RQ1 and RQ2 by designing, implementing, and conducting the first empirical study. The second part addressed RQ3-RQ5 through a second empirical study that asked participants to carry out location-finding tasks with different simulated levels of GPS accuracy.

The following steps were carried out:

Study 1

- Analyse Location Data

To determine the quality of location data, both accuracy and precision were assessed by calculating error and analysing its distribution using data visualisations.

- Identify Factors Affecting Location

Location data is significantly affected by various external factors such as testing location, testing time, testing device and its settings, and weather conditions. The effects of these factors were identified by experimenting with different testing locations, time of day, season of the year, testing devices, and various device settings before finalising them for the study design.

- Design an Empirical Study

In order to determine the impact of the various external factors on the location data, an empirical study was designed. The study design involved gathering location data across different device settings.

- Develop Study System

Based on the study design to assess the effects of external factors on location data, a mobile map application was developed to gather data for a selected target location.

- Analyse Location Data

The collected data from the study was analysed to determine baseline accuracy levels that can be used in the design of the second study.

Study 2

- Determine Accuracy Levels

Results from the first study, as well as the pilot study and pre-study conducted for the second study, were used to determine the number of accuracy levels to be evaluated. Determining accuracy levels is equivalent to establishing a set of error rates to be introduced in each accuracy level.

- Determine Study Tasks

Agricultural field research tasks of location-finding of test plots were designed that could be feasibly carried out by participants in a test field setup. The number of location-finding tasks per experimental condition, where each experimental condition is based on an accuracy level, were determined. This part also included establishing the various qualitative and quantitative measures that needed to be recorded during the study sessions.

- Design Second Study

An empirical study was designed to gather data on the effects of reduced location accuracy on the user task of location-finding.

- Develop Study System

A custom mobile map application with two application modes—one to be operated by the researcher and the other to be operated by the study participant—was developed for the study.

- Prepare Field Testing Area

The testing site for the outdoor study was prepared to simulate agricultural field plots. Temporary plot markings were installed on the ground using custom-made flag stakes on the days of study sessions with participants.

- Conduct Study to Gather Data

Participants for the study were recruited from the university student pool and required data was gathered, which was then analysed to determine the effects of reduced location accuracy on user behaviour and their use of the mobile map application for carrying out location-finding tasks.

1.4 EVALUATION

Two outdoor studies were conducted to evaluate the quality of smartphone location information and the effects of reduced location accuracy on user performance and experience during location-finding tasks in an agricultural field research scenario.

Study 1 revealed significant variations in location accuracy and precision across different device settings and sky cover conditions. Location data from four different device settings conditions was compared to identify the settings that provided the highest accuracy and precision. The data collected under airplane mode demonstrated higher accuracy and precision compared to other settings. Sky cover conditions were analysed to investigate their effect on location data. The analysis showed that the lowest accuracy and precision were observed on days with broken cloud cover under all device settings conditions.

Study 2 utilised a simulated location system with varying accuracy levels. User performance (task completion time and error count) and their subjective experiences were evaluated for the use, trustworthiness, perceived accuracy, and usefulness of location information. Qualitative data analysis was conducted on responses to open-ended questions in the demographics questionnaire and subjective questionnaire. NASA-TLX responses assessed participants’ perceived effort, frustration level, and performance. Subjective responses gathered through a post-study questionnaire regarding participants' strategies and perceptions of accuracy levels throughout the study were also evaluated using formal qualitative analysis.

The key findings from Study 1 highlighted the significant impact of airplane mode on location accuracy and precision. An average accuracy error of 3.88 metres was computed for data collected under airplane mode, indicating no need for network connectivity to achieve high accuracy. The results informed the baseline accuracy levels for the design of the second study.

The key findings from Study 2 revealed that increased error in location accuracy negatively affected both user performance and experience measures. The accuracy threshold was equivalent to the plot edge length, and when the error exceeded this threshold, task completion time and user errors increased significantly. Participants also adapted various strategies to cope with location inaccuracy during the tasks with high error rates.

1.5 CONTRIBUTIONS

The primary contribution of this thesis is new knowledge about mobile GPS accuracy and its limitations in agricultural field research. The results of the studies provide empirical evidence on the effects of reduced location accuracy on the location-finding tasks performed by the participants in a research field-work scenario. The results highlight the need to understand the impact of insufficient location accuracy of mobile map applications, which can lead to an increase in user error and a decrease in use of the location information as a result of lack of trust in the information.

There are two main secondary contributions of this thesis. The results from Study 2 included observations of the participants' interactions with the study system. The analysis of these observations revealed how participants changed and switched their strategies to complete the tasks, how their behaviour changed with the change in their strategies, and how they correlated the virtual location information with the real-world information to complete their tasks. The new information can help us understand the patterns that users adopt when the location accuracy of the system becomes insufficient for completing location-finding tasks. This knowledge has significant implications for designers and developers of mobile map applications, enabling them to better support users in situations of low GPS accuracy.

Another secondary contribution of this thesis is the design of empirical studies and the mobile software systems developed for research. These tools provide a methodological framework for studying mobile GPS accuracy in the context of agricultural field research in detail and can be applied to other research areas where mobile GPS is used to support location-finding tasks.

1.6 THESIS OUTLINE

This thesis is organised into seven chapters. This first chapter outlines the research topic, the contributions made by this thesis, and the structure of the thesis. Chapter Two presents a review of the related literature on GPS technology, GPS services, and applications in various civilian domains. It provides an overview of the factors affecting location accuracy and the different differential correction techniques used to improve accuracy. It also presents a review of the comparative analyses of GNSS receivers and the use of smartphones as GNSS devices. Chapter Three reports on the methods and results of Study 1, designed to determine location accuracy on a mobile platform. Chapter Four reports on the methods and results of Study 2, which investigated the effects of reduced accuracy on location-finding tasks in an agricultural field research scenario. Chapter Five discusses the findings and outcomes of the two studies conducted for this research. Chapter Six concludes by summarizing the contributions and findings of this thesis and discussing future directions for the research.

CHAPTER 2

RELATED WORK

This research is based on three areas of previous work: GPS technology and its diverse applications across a plethora of civilian domains; the influence of various factors on the positioning accuracy of GPS signals and the different correction methods and techniques utilised to improve the accuracy of GNSS receivers; and an assessment of the positioning accuracy, comparative analyses of GNSS receivers and multi-GNSS navigation performance, and the role of smartphones as GNSS devices and their application in numerous research domains.

2.1 GPS TECHNOLOGY AND APPLICATIONS

2.1.1 GPS and GPS Services

The Global Positioning System (GPS) is a space-based radionavigation system consisting of a constellation of satellites that orbit Earth twice a day and transmit radio signals for continuous worldwide coverage [77]. This technology, which relies on satellite networks to determine the location of objects, has transitioned from its initial military applications to being widely accessible for civilian use since 1983 [40,105]. This transformation was driven by increased demand for civilian applications for navigation and surveying. The discontinuation of Selective Availability (SA) in May 2000 improved the accuracy of GPS for civilian users and provided several benefits in the areas of transportation, emergency services, land resource exploration and management, aviation, recreation, space, and timing [33,66].

GPS is one of the Global Navigation Satellite Systems (GNSSs) that provides space-based positioning, navigation, and timing (PNT) services to users [7,59]. The GPS system provides two levels of PNT service: Precise Positioning Service (PPS) and Standard Positioning Service (SPS)

[106]. PPS is characterised by the broadcast of an encrypted navigation data message, exclusively authorised for military use and inaccessible to civilian users. In contrast, SPS, also known as the civilian GPS service, is freely available to all users worldwide on a continuous basis. The SPS was originally designed to provide civil users with a less accurate positioning capability through SA, is the primary GPS service that upholds high-performance standards, ensuring accurate positioning for all GPS users [21]. Additionally, there is an ongoing development effort for a novel service known as the High Accuracy and Robustness Service (HARS), designed to provide cryptographic protection, robustness, and enhanced accuracy to the GPS user community [75].

2.1.2 Diverse Applications of GPS Technology for Civilians

Today, the GPS technology is accessible in various forms for civilian users, including handheld GNSS receivers, in-vehicle GNSS units, and embedded GNSS modules in electronic devices [45]. These low-power, low-cost GPS receivers process the signals transmitted from the satellites to determine geocentric coordinates. Handheld GNSS receivers are portable devices designed for navigation and location-based applications and are typically used for outdoor activities such as hiking, camping, and geocaching for their ability to provide precise location data in challenging terrains and conditions. In-vehicle GPS receivers are used to determine the absolute position of a vehicle and provide navigation assistance to drivers. GPS is also employed for locating and tracking vehicles by vehicle monitoring facilities and fleet dispatchers, monitoring vehicle usage. Additionally, public safety departments use GPS to locate workers in emergency situations [28,45].

The embedded GNSS modules are miniature receivers integrated into a variety of electronic devices such as smartphones, tablets, laptops, and IoT (Internet of Things) devices. These modules enable location-based services and GPS functionality, including navigation, surveying and mapping, location sharing, geotagging, and fitness tracking [28].

2.2 GPS POSITIONING ACCURACY AND OPTIMISATION

2.2.1 Factors Affecting GPS Positioning Accuracy

Despite advancements, the accuracy of GPS remains subject to multiple factors such as satellite geometry, signal blockage, atmospheric conditions, receiver design, and multipath [86,104]. Satellite geometry is affected during maintenance or manoeuvres, resulting in an unevenly distributed set of satellites and creating temporary gaps in coverage. GPS positioning accuracy can also be degraded by satellite signal blockage due to buildings, trees, bridges, and other objects that can obstruct GPS signals. The amount of blockage depends on the environment, with urban areas typically experiencing more blockage than rural areas.

Signal delays and errors are caused by various atmospheric conditions. Ionospheric refraction can lead to fluctuations in GPS signals, resulting in signal loss or degradation, which makes it challenging for the receiver to accurately compute location. Tropospheric delays are influenced by factors such as temperature, pressure, cloudiness, precipitation, and humidity. Additionally, solar activity also plays a role in accurate position determination [16,49,50,61].

The quality and design of a GPS receiver play a critical role in determining location accuracy. Receivers equipped with high-quality, well-designed antennas and processors can receive signals from a larger number of satellites simultaneously, providing more accurate positions. Additionally, they can reduce signal interference, improve signal reception, apply advanced signal processing to mitigate errors, and exhibit sensitivity to weak signals [27,66]. These characteristics contribute to more accurate and reliable position information, particularly during real-time tracking [28]. Multipath is another error source that occurs when GPS signals sent by satellites are reflected off nearby surfaces, such as buildings, trees, or areas with potential multipath sources, such as dense vegetation or urban canyons, before reaching the GPS receiver antenna. These reflected signals can interfere with the direct signals from the satellites, causing a time delay in the reflected signal, thereby introducing errors and inaccuracies in GPS positioning [9,46].

2.2.2 Optimising GPS Accuracy through Differential Corrections

Differential correction techniques have been developed to mitigate factors affecting the accuracy of GPS positioning. These techniques are applicable in real-time or during the post-processing of data and are transmitted to rover receivers through correction signals [69]. These correction signals are primarily broadcast via standalone reference stations or geostationary communication satellites [51]. Real-time differential correction methods, such as Differential GPS (DGPS) and Real-Time Kinematic (RTK), utilise standalone reference stations [39,43]. These stationary reference stations, with known coordinates, calculate error correction data, which represents the difference between the positions indicated by the satellites and the known fixed positions. Thereafter, this correction data is broadcast by these base stations to the rover GPS receiver, improving its accuracy and providing differentially corrected positioning [51]. Satellite-Based Augmentation Systems (SBAS), such as WAAS (Wide Area Augmentation System) in the United States, EGNOS (European Geostationary Navigation Overlay Service) in Europe, GAGAN (GPS Aided Geo Augmented Navigation) in India, and MSAS (Multi-functional Satellite Augmentation System) in Japan, use geostationary communication satellites to transmit correction data to GNSS receivers [43,51]. Assisted-GNSS (A-GNSS) in smartphones facilitates faster Time to First Fix (TTFF) and higher sensitivity — that is, an enhanced ability to detect and work with weaker or obstructed satellite signals, leading to improved GPS performance and accuracy, especially in challenging or unfavourable conditions [23,24]. A-GNSS offers assistance data to the receiver, typically through wireless networks, commonly utilising a cellular data channel or Wi-Fi. A-GNSS relies on a network of GNSS reference stations and location servers that aggregate data from these stations and distribute it over wireless networks (Figure 2.1). While the A-GNSS receiver requires additional range measurements from GNSS satellites, the A-GNSS system accelerates the process of determining position [24].

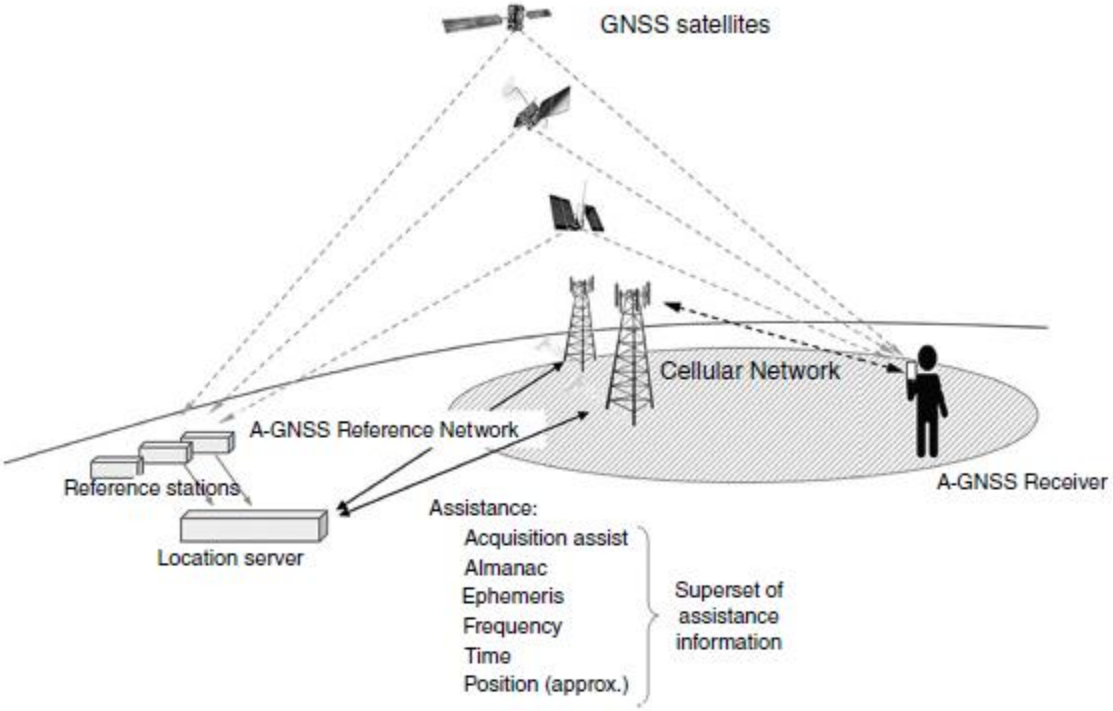


Figure 2.1: A-GNSS system overview [24].

Post-processing differential correction methods, including Precise Point Positioning (PPP) and Post-Processing Kinematic (PPK), collect raw satellite signal data alongside the rover GPS receiver's position data. Subsequently, correction data received from the reference stations is used during post-processing to calculate highly accurate positions [20,26,43,73].

2.3 GNSS RECEIVERS AND SMARTPHONE INTEGRATION

2.3.1 Assessment of GNSS Receivers in Real-World Conditions

Studies evaluating the accuracy of GNSS receivers in real-world field conditions have provided valuable insights. Rychlicki et al. [80] conducted a comprehensive study comparing the within-field accuracy and reliability of nine popular consumer-grade GPS receivers. The findings revealed that receivers utilising dual-frequency (L1/L2) satellite signals demonstrated the lowest Dilution of Precision (DOP), including Horizontal DOP (HDOP) and Vertical DOP (VDOP), resulting in higher positioning accuracy. Catania et al. [15] conducted a comparative analysis of the positioning accuracy of four GNSS receivers, employing external antennas and RTK differential correction. The study aimed to determine the influence of correction techniques on the achieved positioning accuracy. The results emphasised the significant enhancement in positioning accuracy achieved by employing both an external antenna and the RTK differential correction technique. Notably, a low-cost L1 frequency receiver exhibited a mean positioning error of only 0.0550 metres. The study highlighted the importance of using the RTK differential correction technique and an external antenna to achieve higher positioning accuracy that is possible with low-cost devices such as those described in the paper, which have the potential for aiding farmers in meeting their precision agriculture requirements and assisting researchers in agricultural field research. For example, high-resolution topographic data (HRTD) holds pivotal importance across diverse domains, including urban planning, disaster management, environmental monitoring, and agriculture. Obtaining such data involves leveraging GNSS technologies alongside various correction techniques such as RTK, PPK, and PPP [26,35,89,96].

A number of experiments were conducted to study the effects of the multi-GNSS function on the receivers' performances in addition to examining the various differential correction methods. Chen et al. [42] conducted a comparative analysis of navigation performance by combining multiple positioning technologies. The research concluded that “the combination of GPS + GLONASS + Galileo has the best performance in terms of availability, coverage and continuity”. Additionally, Li et al. [54] proposed a four-system (BeiDou + Galileo + GLONASS + GPS) positioning model that significantly improved accuracy in precise positioning. Recent studies by Li et al. [53], Sheta et al. [81], Yan et al. [94], and Mostafa et al. [60] have also explored the advantages of integrating smartphone GNSS signals with other navigation sensors.

2.3.2 The Ubiquity of Smartphones as GNSS Devices

Smartphones serve as ubiquitous, low-cost handheld GNSS receivers, potentially replacing traditional GPS devices. They offer a cost-effective and efficient alternative for achieving high positioning accuracy in fieldwork [2,3]. The GNSS capabilities of smartphones have significantly evolved over the years. In the early 2000s, mobile phones started featuring built-in GPS receivers. The Benefon ESC!, launched in 1999, is regarded as one of the first mobile phones with integrated GPS capability and built-in maps [107]. Over the last two decades, GPS technology embedded in smartphones has seen exponential advancement. In 2018, Xiaomi Inc. introduced the world’s first dual-frequency GNSS smartphone, the Xiaomi Mi 8 [30]. The dual-frequency implementation [52] integrates both L1 and L5 bands, providing faster and more accurate GPS data. The improvement in GPS accuracy can be attributed to various advancements in both hardware and signal processing algorithms over the years [79]. Smartphones now utilise more sensitive GPS receivers capable of receiving signals from multiple satellites, enabling precise location approximation. In the early stages of incorporating GPS chips into smartphones, GPS signals could only be picked up when the sky was clearly visible. However, in recent times, many smartphones can receive GPS signals indoors and in areas where GPS transmissions are limited. While older smartphones took a few seconds to lock onto GPS satellites, the majority of modern smartphones accomplish this within a fraction of that time. Modern smartphones have expanded their capabilities to offer a wide range of location-based services, including locating nearby businesses, tracking fitness activities, and providing weather updates. This stands in contrast to early mobile phones that were primarily limited to basic navigation tasks. GPS accuracy has significantly improved, evolving from approximately 100 metres in early mobile phones to less than 5 metres in most recent models [25,30,33].

2.3.3 Advancements in Smartphone GNSS Chipsets for Precise Positioning

Studies conducted with smartphones, equipped with both single- and dual-frequency chipsets, have demonstrated that achieving precise positioning is possible, especially with smartphones equipped with dual-frequency GNSS chipsets. The work presented by Paziewski et al. [68] showcases the feasibility of using recent Android smartphones to obtain precise centimetre-level positioning accuracy. Dual-frequency smartphones performed comparably to geodetic receivers in terms of GNSS signal tracking capability. The dual-frequency Android smartphones are equipped with GNSS chips and antennas capable of tracking multi-frequency, multi-constellation data, thereby providing high-level positioning accuracy [30,76,92]. Additionally, smartphone applications were found to be more intuitive with a rapid learning curve compared to learning the operation of dedicated GPS devices [47].

While the majority of available smartphones are embedded with single-frequency GNSS modules, recent advancements in multi-constellation and multi-frequency signals have enabled precise positional information obtainable not only from high-grade geodetic receivers and the latest dual-frequency GNSS receiver-equipped smartphones but also from handheld low-cost receivers and single-frequency smartphones [67]. The positioning accuracy of single-frequency smartphones can be enhanced by utilising correction methods such as RTK [62] and NRTK [18] in situations where greater positioning accuracy is required.

Stanford University's GPS MOOC used smartphones to collect data on GNSS accuracy in a variety of environments. The experiment saw participation from thousands of individuals spanning 192 countries, made possible by the widespread availability of smartphones equipped with GNSS receivers. The data collected on GNSS accuracy through smartphones was then analysed to determine the mean accuracy. The results reported the mean accuracy of 4.9 metres in open-sky environments [25]. In a study by Merry et al. [57], it was found that the time of year did not influence GPS accuracy on a smartphone; however, the time of day had an effect, with improved accuracy observed in the afternoon.

2.3.4 Leveraging Smartphones for Location-Based Information Collection

Numerous studies have utilised smartphones for mobile map-based human navigation, object tracking, and location-based information collection regarding human behaviour and patterns. A comparative study evaluating location data obtained from GPS devices and mobile phones concluded that GPS-enabled mobile phones are efficient at measuring outdoor activity and travel, and tracking time and visits to specific locations [34]. Rout et al. [78] collected smartphone GPS data to analyse human spatial behaviours within urban environments. Brynes et al. [12] investigated adolescent proximity to drinking and marijuana outlets using GPS-enabled smartphones to understand travel patterns and time spent near these outlets. Smartphone-based GPS tracking was employed to monitor the real-time movement of 472 tourists via a mobile app, providing valuable insights into tourists' travel behaviour [37]. A study by Olson and Wagner [63] tested the integration of GPS-enabled smartphones for interviewers in face-to-face surveys, examining its impact on interviewer behaviour, compliance with GPS requests, data quality, and potential implications for future monitoring and understanding of interviewer travel behaviour in survey efforts. A study on smartphone GPS tracking to analyse recreational movement patterns in urban forests utilised GPS data collected from users' existing sports tracking applications on their mobile phones, offering insights into visitor spatial behaviours and identifying hotspots of off-trail movement [48]. Smartphone GPS tracking was conducted to understand the activity spaces of older adults in residential and non-residential environments [95]. Geospatial activity data, such as movement patterns and location changes, through smartphone GPS tracking also helped monitor individuals’ mental well-being [6] and collect behavioural data [36] as part of their daily activities and mobility patterns.

Smartphones have found extensive application in field studies, particularly in agriculture. Smartphone applications have been employed in various agricultural domains, including crop diagnosis, weed identification and treatment, fertilisation application, yield estimation, disease detection, and more [85]. Smartphones offer cost-effective alternatives for crop monitoring, diagnosis and plant phenotyping [1], crop health evaluation and yield estimation [91], real-time foliage damage monitoring [55], plant disease diagnosis [70,71], plant segmentation and crop image analysis [32,41,91], pesticide spraying analysis and sprayed collector coverage [31,56], fertiliser selection and cost optimization [11], irrigation scheduling [32,72,90], water conservation [44,58], and canopy growth and architecture [4,5,65]. GPS is one of the most popular smartphone sensors used in precision agriculture [74]. However, in many mobile applications, smartphone GPS capability serves as a valuable measure only for data logging, aiding in GIS mapping and adding contextual location information to databases [5,58,71,84,91]. Some studies have demonstrated smartphone GPS' use for obtaining positioning information for various agricultural fieldwork purposes. Smartphone GPS was tested in comparison with other GNSS devices in forests during leaf-on and leaf-off conditions and it was found that current smartphones' real-time horizontal accuracy is comparative to some of the consumer-grade and mapping-grade receivers under open area conditions [87]. Smartphone positioning capability was explored in a study by Caicong et al. [13] with the aim of monitoring farm operations. An Android app was developed to assist field biologists to locate plots in a field by using distance calculation and field notes without relying on location services, with the optional use of GPS assistance [8].

CHAPTER 3

STUDY 1: SMARTPHONE GPS ACCURACY AND PRECISION

Study 1 was designed to understand the quality of location data received by a GPS-enabled smartphone. The study focused on determining the accuracy and precision of location measurements for a single point of reference on the ground. A location coordinate consisted of latitude and longitude values which were collected across four different device settings to determine the most reliable conditions that could provide the highest location accuracy and precision on a smartphone.

3.1 RESEARCH METHODS

This section describes the study system, experimental conditions, procedure, tasks, and study design.

3.1.1 Study System

A custom Android application was developed to collect location data across four different experimental conditions. These conditions required changes in the smartphone's location and network settings. The purpose of collecting location data with the different settings was to compare the accuracy and precision of location measurements from the different conditions and identify the device settings that provide the most accurate and precise location data. The application used Google Maps and displayed a location marker indicating the current location of the smartphone, which was held by the experimenter. The testing and data collection was carried out outdoors in an open area with clear view of the sky for a specific target location over the course of twelve days.

A native Android app was developed in Java, utilising the Google Maps SDK, the Google Play Services Library, and OpenWeatherMapLib to access Google Maps, the device's location, and weather data. LG G6 Android smartphone equipped with Qualcomm Snapdragon 821 chipset, running on Android 9 (Pie) was used for the study. With prior familiarity with Android development, the Android platform was used to develop the map application for the study.

Figure 3.1 shows the application interface for the study system. The current user location is depicted by the triangular blue marker in the centre of the map view. On the upper right of the map interface, a text view shows the location updates that are fetched every second. In order to store the location measurements for each round, the ADD button at the bottom of the screen creates a JSON object. The number of rounds stored at any given point during the experiment is shown in the text view to the left of the ADD button. The SAVE TO JSON button was used to save the location data to the phone's internal memory storage at the conclusion of data collection for all the rounds of an experimental condition.

Figure 3.1: Map application interface of the study system.

3.1.2 Experimental Conditions

To determine the effects of various device network and location settings on the accuracy and precision of GPS data received, the following four experimental conditions were selected for collecting location data for the study:

- *LocationOnly*: Only the device location setting was enabled for the smartphone. This setting only uses GPS for fetching location.

- *Location+WiFi*: Location and Wi-Fi were both enabled in this case. These settings make use of both the GPS and Wi-Fi network (i.e., using Wi-Fi access points) for location.

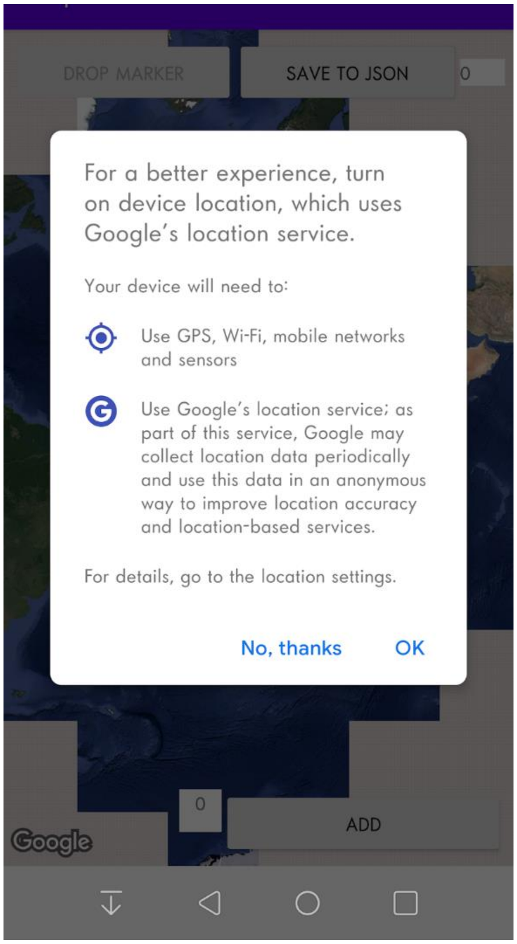
- *Location+MobileData*: Location and mobile data network were both enabled in this case. These settings use both the GPS and mobile data (i.e., using cellular tower locations) for location.

- *Location+AirplaneMode*: Location services were enabled, and airplane mode was switched on to prevent Wi-Fi or mobile data access.

Although GPS accuracy was expected to be the same in airplane mode as when only device location is enabled on the smartphone, improved location accuracy and precision results were recorded during the pilot testing. Therefore, *Location+AirplaneMode* condition was included as one of the experimental conditions. The possible reason for the results is that airplane mode eliminates all signal interruptions that can interfere with the GPS signal, which can improve accuracy and precision in areas with a lot of Wi-Fi and Bluetooth signal obstructions or in suboptimal atmospheric conditions.

A fifth experimental condition—where all three settings (device location, Wi-Fi and mobile data) were enabled at the same time—was also tested during the piloting of the study. It was found that when both Wi-Fi and mobile data were enabled on the smartphone and the Wi-Fi signal strength was excellent, it took precedence over the mobile data network; only in the case of weak Wi-Fi reception did the testing system switch to the mobile data network for receiving location. As a result, this device settings condition was not included as one of the experimental conditions.

In each experimental condition, the location setting was enabled to allow the device to receive signals from the satellites broadcasting location information to the GPS receivers of the device. Figure 3.2 shows the device location permission that needs to be granted before using the app for collecting location data during the study.



For a better experience, turn on device location, which uses Google's location service.

Your device will need to:

Use GPS, Wi-Fi, mobile networks and sensors

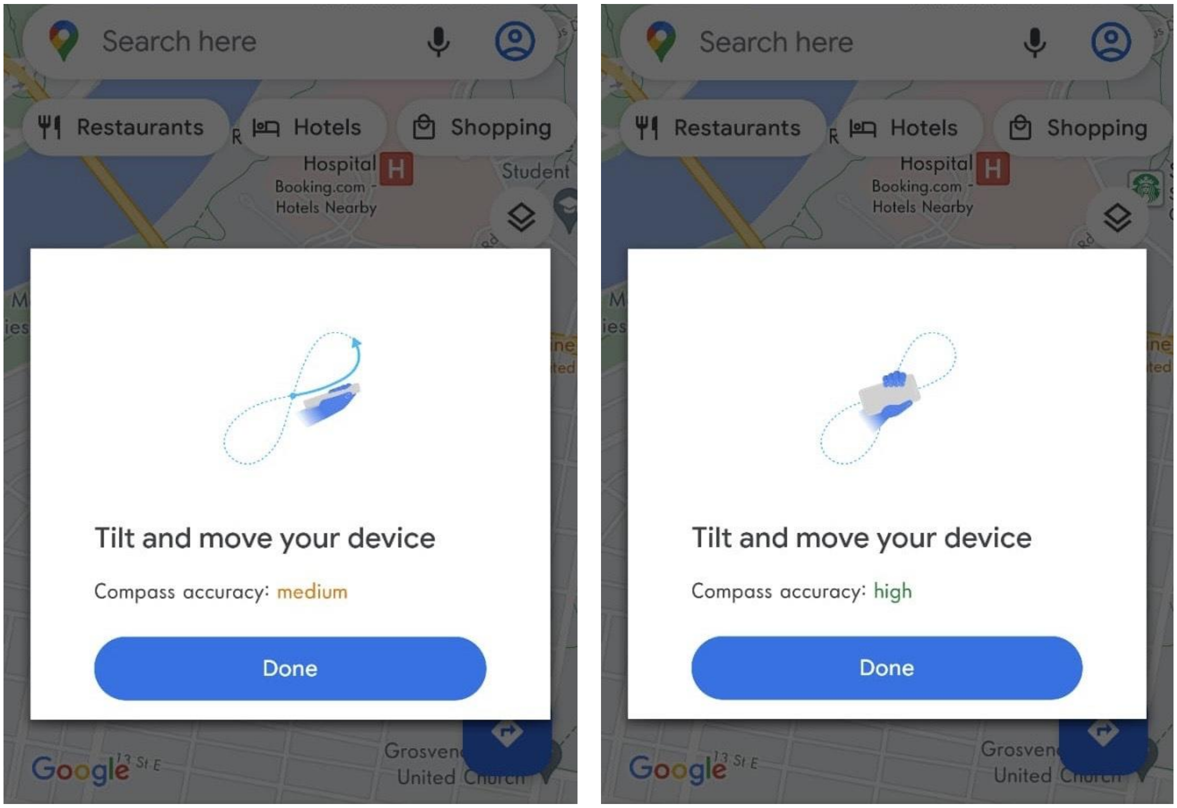
Use Google's location service; as part of this service, Google may collect location data periodically and use this data in an anonymous way to improve location accuracy and location-based services.

For details, go to the location settings.

Figure 3.2: Device location permission dialog box on app startup to enable Google's location service for gathering location data in the app.

3.1.3 Procedure and Study Task

For the experiment, a starting and a returning point were selected on the ground approximately 22 metres apart. Prior to the process of data collection for each experimental condition, phone calibration was performed to ensure the data were collected for the correct location. The figure-of-eight compass calibration was performed using Google Maps [108]. Figure 3.3 shows the compass accuracy status before and after calibration.



Tilt and move your device

Compass accuracy: medium

Tilt and move your device

Compass accuracy: high

Figure 3.3: Compass accuracy before and after calibration. The left image shows that the compass accuracy was medium before calibration, while the right image shows that the compass accuracy was high after calibration.

The testing method was to hold the smartphone stationary and stand at the starting point to record 30 location measurements that were logged as one round. The location measurements were recorded each second and therefore each round took thirty seconds to complete. Before starting a round, a few seconds pause was taken to allow the location marker to adjust itself to the starting point's location on the on-screen map. This allowed the device GPS receivers to correctly determine the device location and start receiving GPS signals for that location. The time interval between each subsequent round was approximately 45-55 seconds, which was calculated by adding the time it took to walk to the returning point and back to the starting point and the time that was allowed for the marker to adjust to the starting point.

Ten rounds of data collection were performed for each of the four experimental conditions. A total of 1,200 location measurements were collected for each condition on each day (30 location measurements per round x 10 rounds x 4 experimental conditions = 1200). Data was collected on 12 successive days, for a total of 1200 x 12 = 14,400 location measurements. The experiment was performed at approximately 1:00 PM each day to maintain consistency in experimental conditions. The multiple rounds per experimental condition were conducted to reduce the effect of any variance caused by environmental conditions or experimenter actions. The time interval between each subsequent experimental condition was the time taken to change device settings and perform phone calibration before the start of the next condition.

3.1.4 Study Design

The following research questions were addressed with Study 1:

- RQ1: Do different network and location settings of a smartphone affect the accuracy and precision of the location data received?
- RQ2: Which device settings are ideal for receiving the most accurate and precise location data?

Location measurements were recorded for each location update received by the device. Each measurement contains a latitude and longitude value that can be compared to the known location used in the study (that is, the fixed location for which the location data was collected) referred to as true location in this chapter. To evaluate the accuracy and precision of location measurements, errors in both these measures were computed, and the error distribution was analysed using graph visualizations.

Accuracy: Measure that quantifies how close the location measurements are to the true location.

Precision: Measure that quantifies how close the location measurements are to each other.

Therefore, high accuracy implies that the measurements cluster around the true location and high precision implies low variability among the measurements that cluster close to each other.

The dependent variables measured for each round of an experimental condition were:

- *Accuracy Error*: Mean distance to the true location—the mean of the distances between each of the thirty measurements of a round and the true location.

- *Precision Error I*: Mean distance to the mean location of a round—the mean of the distances between each of the thirty measurements of a round and the mean of that round.

- *Precision Error II*: Mean distance to the mean location of the first subset of a round—the mean of the distances between each of the fifteen measurements in the second subset and the mean of the first subset of that round. To determine Precision Error II for each round within an experimental condition, the thirty location measurements from each round were divided into two distinct datasets, each consisting of fifteen measurements.

  The distance calculations performed between any two location coordinates were computed using the Euclidean distance formula [64]. The error values are reported in metres.

High error in accuracy and precision corresponds to low accuracy and precision for a round.

For each measurement session per condition each day, information about the weather conditions was also recorded to determine whether there was any effect of sky cover conditions on accuracy or precision of location data.

3.2 RESULTS

The following subsections report on the study's findings and the dependent measures listed in Section 3.1.4. Among the four experimental conditions, the *Location+AirplaneMode* condition had the highest accuracy and precision. The sky cover conditions also had an effect on the location data: higher accuracy and precision were recorded on days with better sky cover conditions than on overcast days (see Tables 3.4 and 3.5).

3.2.1 Location Data

The location data for each condition was collected over twelve days and each day consisted of 300 location measurements per condition. The following figures show the location measurements collected for the four conditions on one of the testing days. Figures 3.4, 3.6, 3.8 and 3.10 show scatterplots for each condition with 300 location measurements from ten rounds. Latitude and longitude values were used to calculate and plot the location data points with reference to the true location where the location data was recorded. A red circle at the centre of the charts denotes the true location (the starting location); ten different coloured clusters of data points represent each round’s location measurements with a corresponding triangle of the same colour that represents mean location value for the round; and the red asterisk represents the mean of all of the ten triangles from the ten rounds. Figures 3.5, 3.7, 3.9 and 3.11 display a detailed view of the scatterplots, visualising data from the ten rounds individually. The true location is denoted by the red circle at the centre of the charts, the cyan triangles represent the mean location for the rounds, and the black circles indicate the thirty location data points collected in each round.

Figures 3.10 and 3.11 from the *Location+AirplaneMode* condition clearly show higher accuracy and precision for each of the ten rounds in comparison to the data from the other conditions. A similar trend was observed in the other days' data where the *Location+AirplaneMode* condition performed better than the other three experimental conditions.

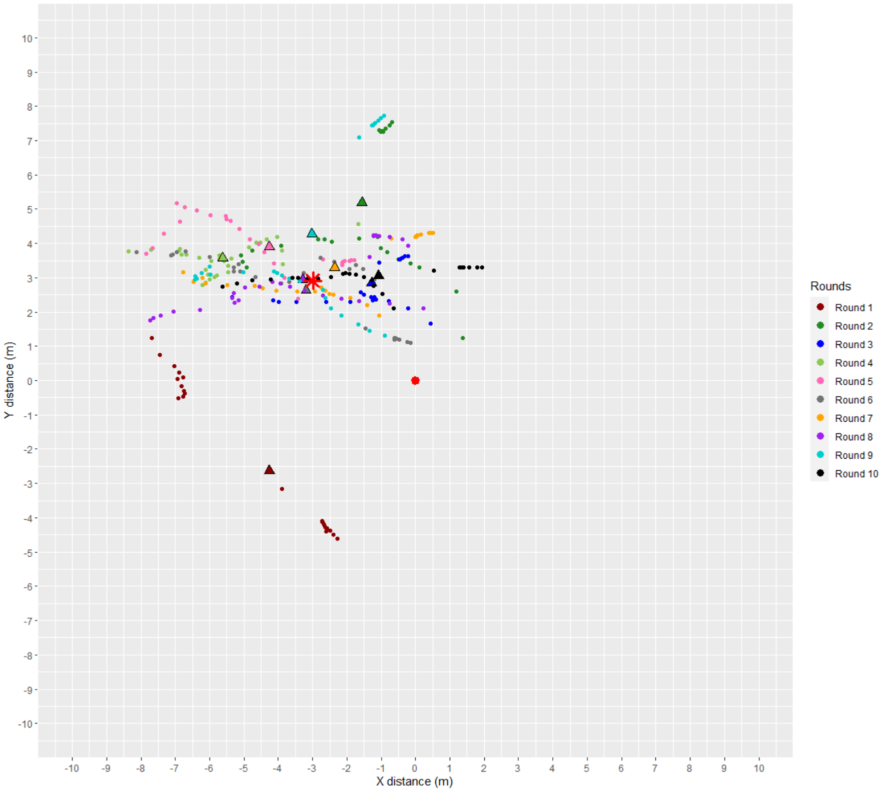
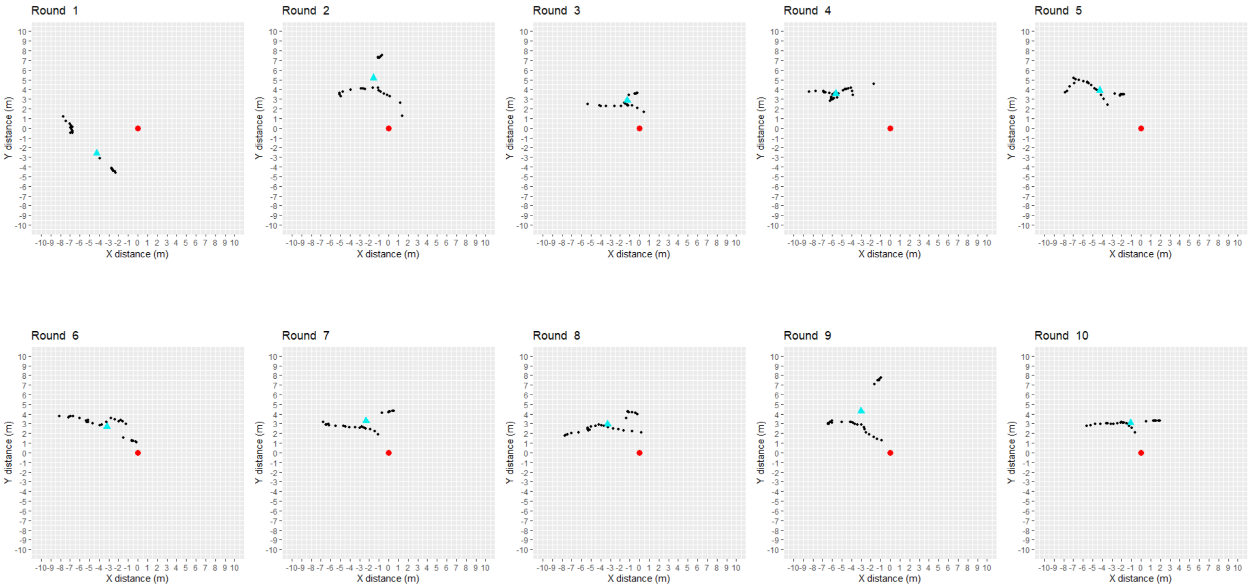


Figure 3.4: LocationOnly condition: location data points from all ten rounds; each round consisting of thirty location measurements.



Round 1
Round 2
Round 3
Round 4
Round 5
Round 6
Round 7
Round 8
Round 9
Round 10

Figure 3.5: LocationOnly condition: a detailed view of the location data points from each of the ten rounds shown in Figure 3.4.

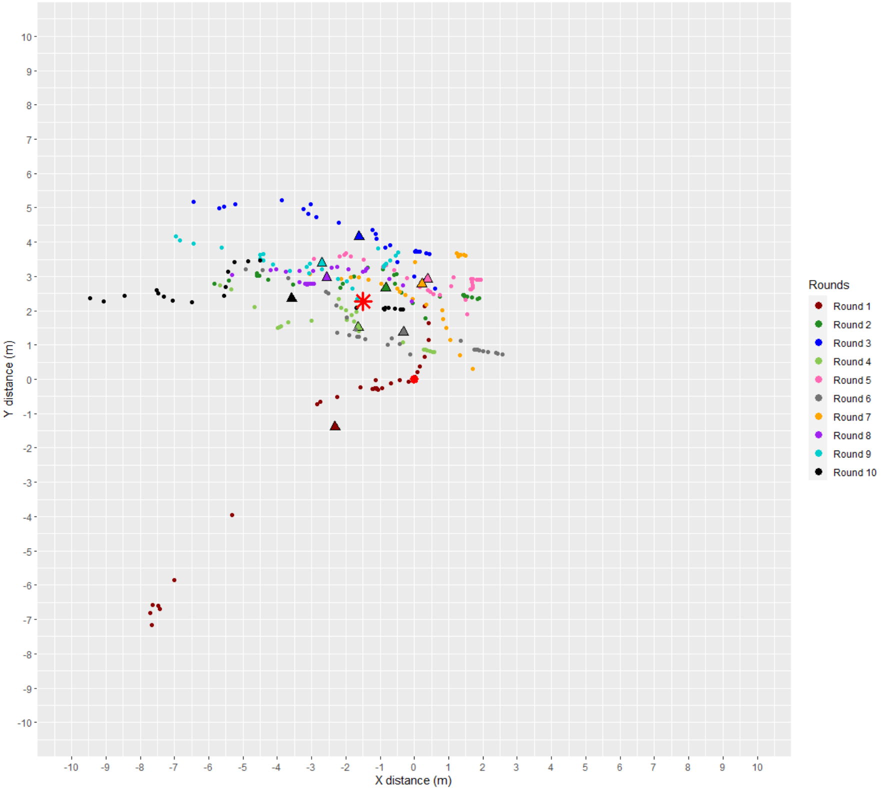


Figure 3.6: Location+WiFi condition: location data points from all ten rounds; each round consisting of thirty location measurements.

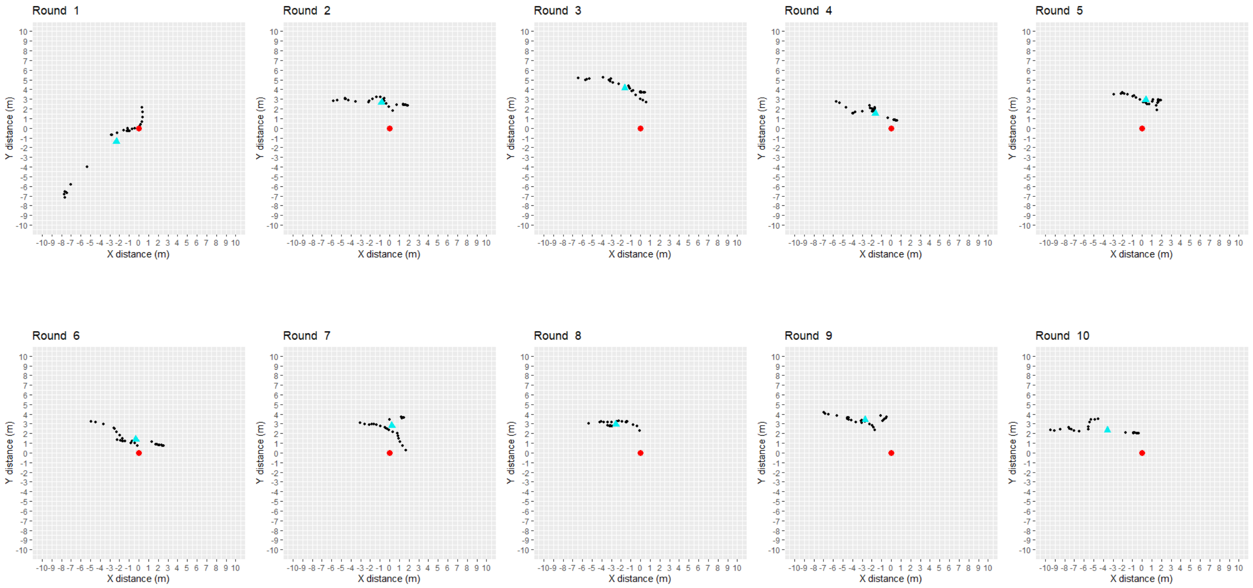


Figure 3.7: Location+WiFi condition: a detailed view of the location data points from each of the ten rounds shown in Figure 3.6.

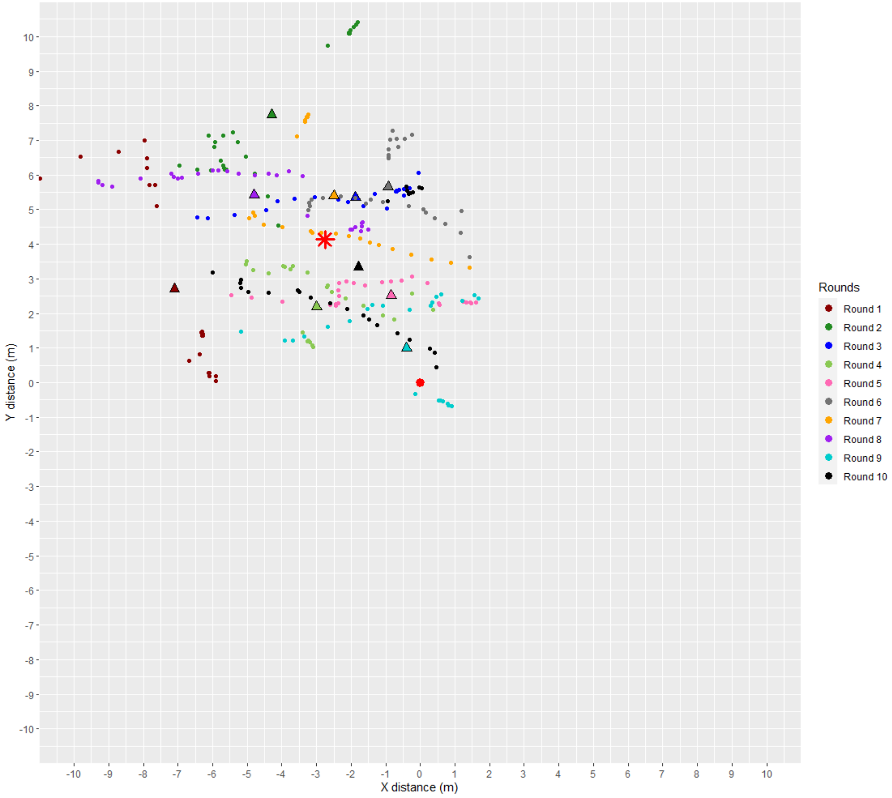


Figure 3.8: Location+MobileData condition: location data points from all ten rounds; each round consisting of thirty location measurements.

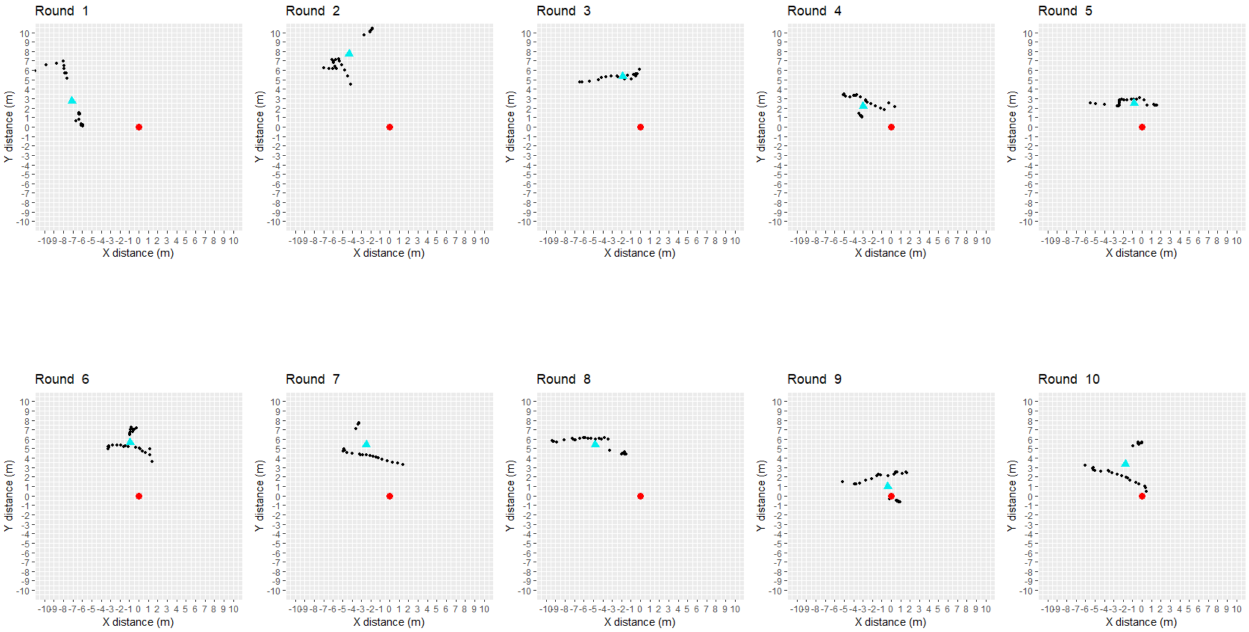


Figure 3.9: Location+MobileData condition: a detailed view of the location data points from each of the ten rounds shown in Figure 3.8.

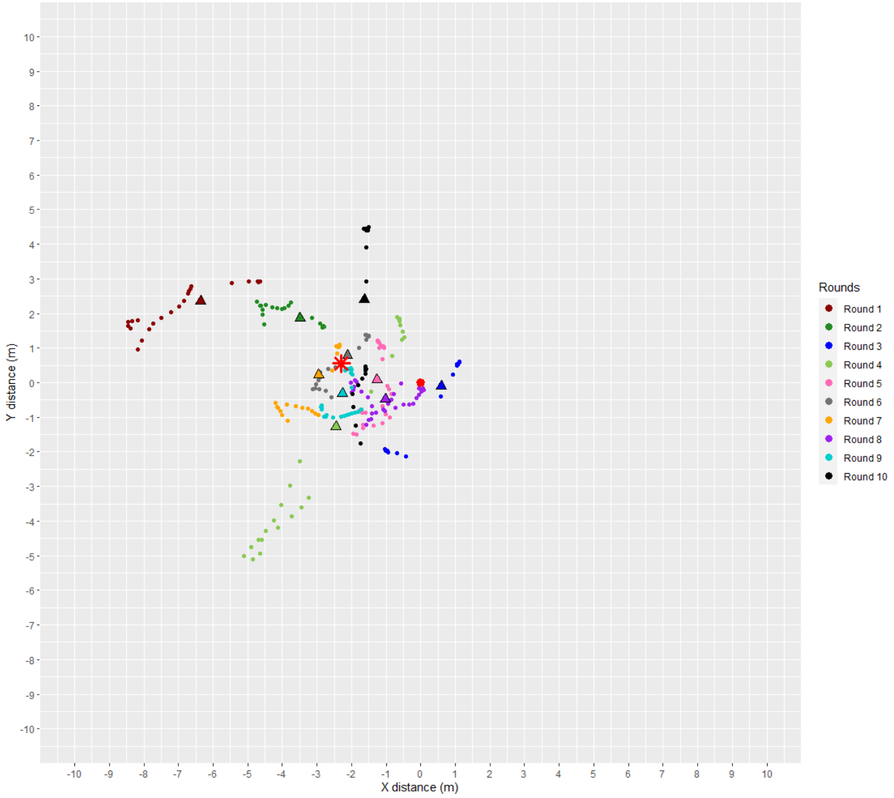


Figure 3.10: Location+AirplaneMode condition: location data points from all ten rounds; each round consisting of thirty location measurements.

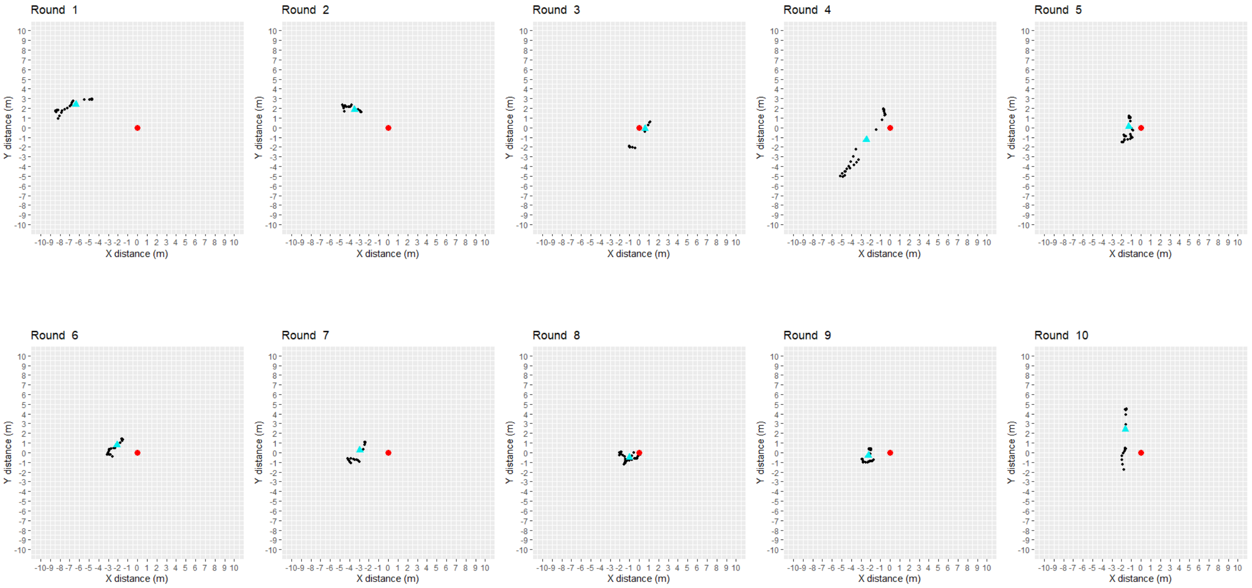


Figure 3.11: Location+AirplaneMode condition: a detailed view of the location data points from each of the ten rounds shown in Figure 3.10.

3.2.2 Accuracy Error

Accuracy Error was calculated for each round, condition, and day of the experiment. For each round, it is the mean of the distances between each of the thirty location measurements of the round and the true location. The mean of the error values from all the rounds of an experimental condition provides the Accuracy Error for the condition, and the mean of the error values of the condition for all twelve days provides overall Accuracy Error for the condition during the entire study period. Table 3.1 shows the Accuracy Error values for all four experimental conditions on all the twelve days. The last row of the table shows the overall Accuracy Error for each condition.

Day	LocationOnly	Location+WiFi	Location+MobileData	Location+AirplaneMode
1	4.9568	4.7590	5.1338	4.3881
2	3.5878	4.4443	5.2530	2.9198
3	5.5910	5.6900	5.6064	4.7564
4	3.6119	4.2140	3.7770	4.8568
5	4.8321	3.9017	5.4332	3.9317
6	7.0111	5.8619	6.0914	4.8371
7	5.0851	3.6021	5.5832	3.0140
8	3.9521	3.9490	4.0927	2.4596
9	5.7632	4.6611	4.3853	4.8776
10	4.3831	4.8779	4.6169	4.0103
11	3.1030	4.5191	4.3849	2.0157
12	3.6946	4.2467	3.8748	4.5044
Mean	4.6310	4.5606	4.8527	3.8810

Table 3.1: Accuracy Error for all four experimental conditions across the twelve days.

The *Location+AirplaneMode* condition has the lowest overall error, 3.88 metres, which tells how far the location was recorded by the device with respect to the true location. Similar observations can be made from individual days' results where the accuracy for most of the days was highest for the *Location+AirplaneMode* condition; this condition's measured location was closest to the true location more than 90 percent of the time.

In Figure 3.12, Accuracy Error is depicted for each of the ten rounds across all four experimental conditions on one of the testing days. The *Location+AirplaneMode* condition demonstrates the highest accuracy in five of the testing rounds compared to the other three experimental conditions.

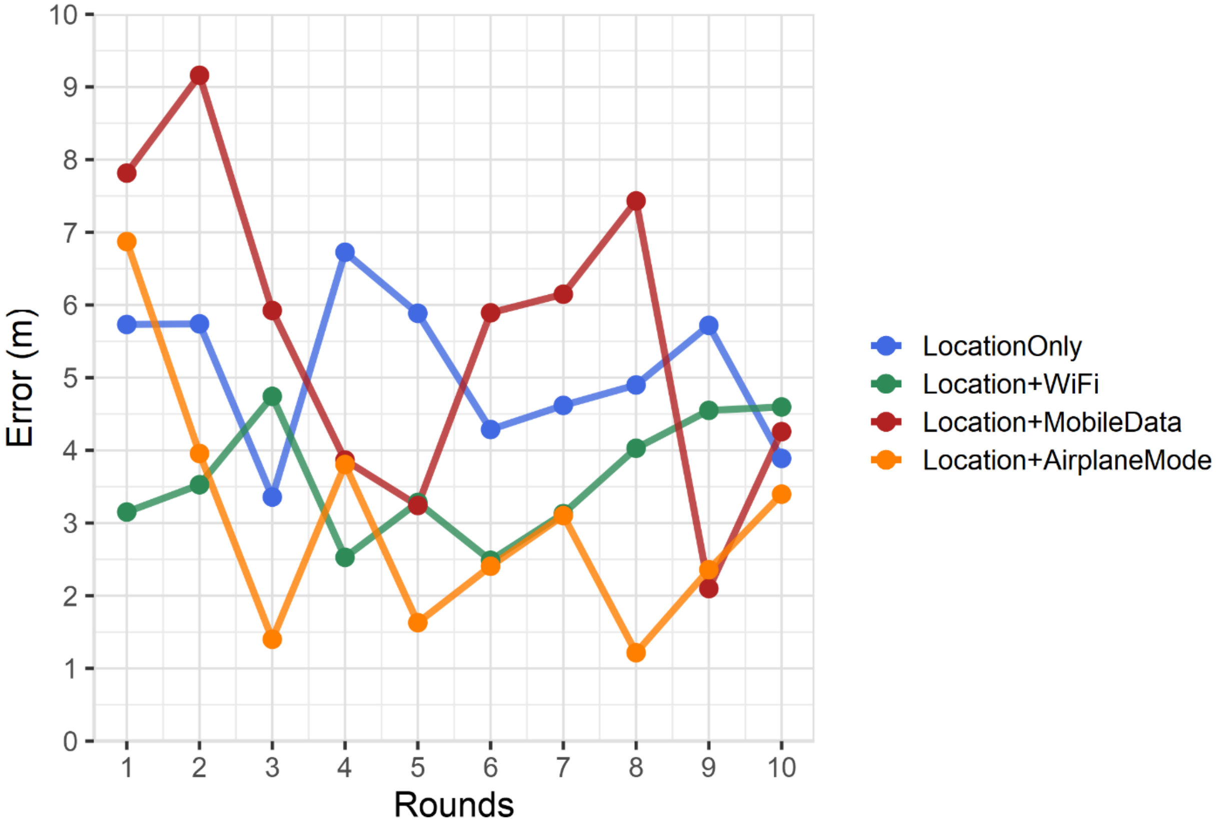


Figure 3.12: Accuracy Error across the ten rounds in each experimental condition.

Two precision error measures, Precision Error I and Precision Error II, were computed to analyse the location data collected for Study 1.

3.2.3 Precision Error I

Precision Error I was calculated for each round to determine the degree of clustering of the location measurements. This reflects the variance among the location measurements collected for the true location. The error values for each round of an experimental condition were computed as the mean of the distances between each of the thirty location measurements of the round and the mean of that round. The mean of the error values from all ten rounds within the experimental condition provides the precision error for that condition. Similarly, the mean of the error values from the experimental condition over all twelve days provides the overall precision error for the condition for the entire study period.

Table 3.2 shows the Precision Error I values for all four experimental conditions on all the twelve days of the experiment. The last row of the table shows overall Precision Error I values for each experimental condition in the experiment.

The *Location+AirplaneMode* condition had the lowest variance across all days, with an overall lowest variance of 0.97 metres, which demonstrates the highest precision recorded among the location measurements in this condition. This indicates that the location measurements were closely clustered together compared to the location measurements recorded under the other three experimental conditions.

The *Location+WiFi* condition shows higher precision for nine of the twelve days than the *Location+MobileData* condition and the *LocationOnly* condition, with an overall variance of 1.69 metres.

Day	LocationOnly	Location+WiFi	Location+MobileData	Location+AirplaneMode
1	2.0113	1.6296	1.9547	1.0593
2	1.6425	2.2308	2.0631	0.9230
3	1.4745	1.8558	1.5880	0.6922
4	1.5032	2.2189	1.9458	1.1416
5	1.6122	1.4908	1.6102	1.1605
6	1.8460	1.6994	1.7800	0.8996
7	2.1496	1.9812	2.0631	1.3368
8	1.9044	1.5935	1.8502	0.8671
9	2.1243	1.3557	1.8127	0.7905
10	1.6352	1.4218	1.7417	1.0321
11	1.4631	1.2551	1.7139	0.9488
12	1.5987	1.5685	1.8102	0.8186
Mean	1.7471	1.6918	1.8278	0.9725

Table 3.2: Precision Error I in all four experimental conditions across the twelve days.

Figure 3.13 presents Precision Error I statistics for all four experimental conditions gathered on one of the testing days. Each line denotes the Precision Error I values for each of the ten rounds of each experimental condition. Figures 3.14-3.17 show the Accuracy Error and Precision Error I data for each of the four experimental conditions individually. The Accuracy Error for each round is represented by a solid circle, with concentric circles of the same colour representing 95% of the data. These outer circles represent two standard deviations of the Precision Error I values for each round.

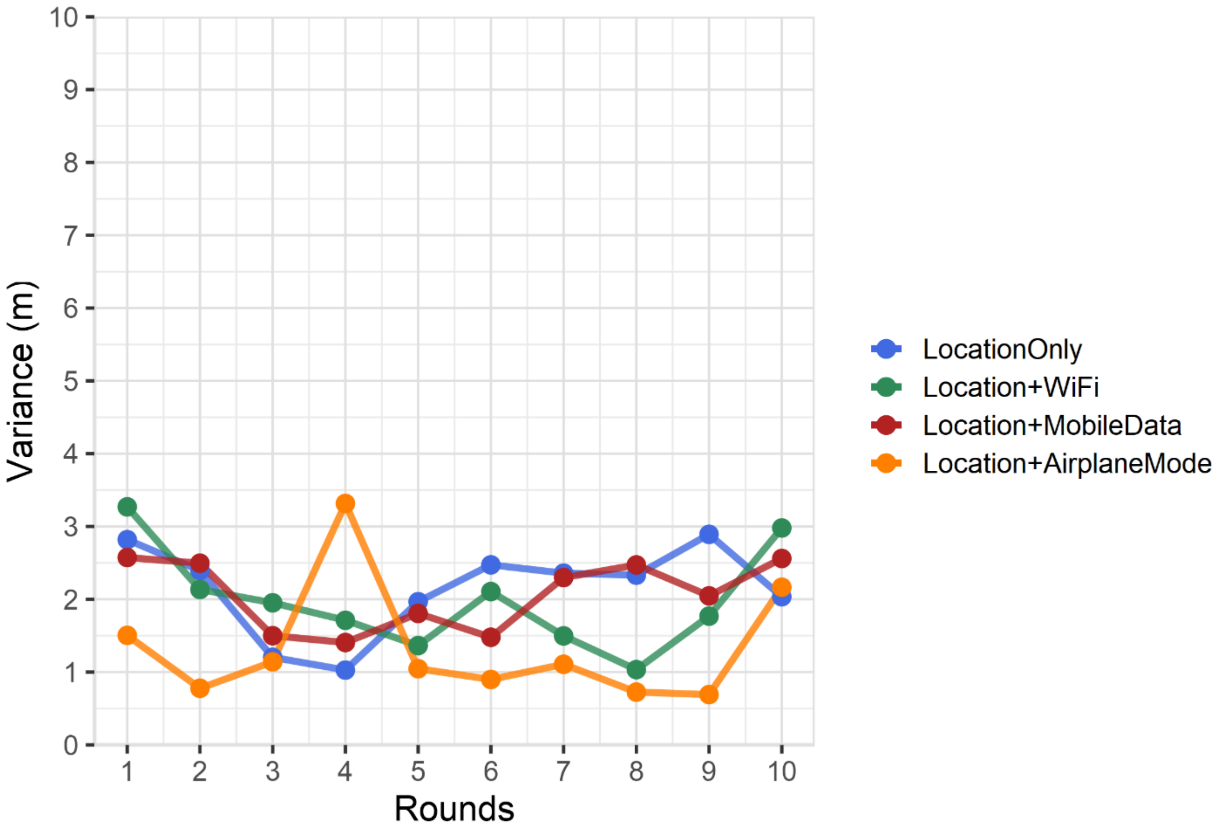


Figure 3.13: Precision Error I across the ten rounds in each experimental condition.

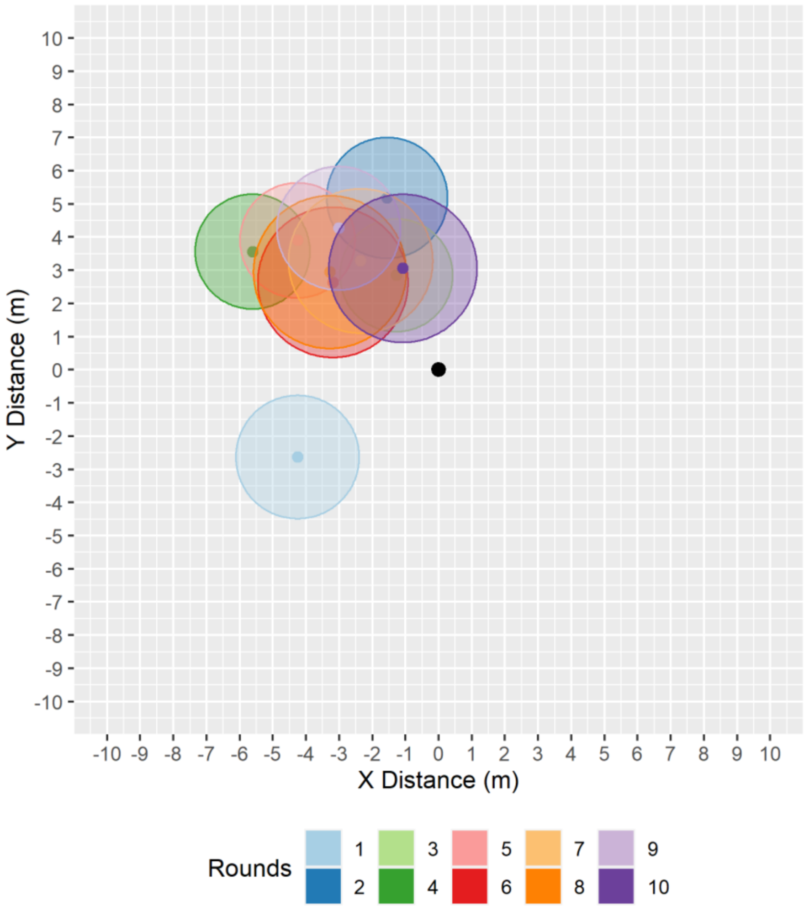


Figure 3.14: LocationOnly condition: the true location represented by the black circle; Accuracy Error represented by solid circles; Precision Error I represented by concentric circles of the same colour.

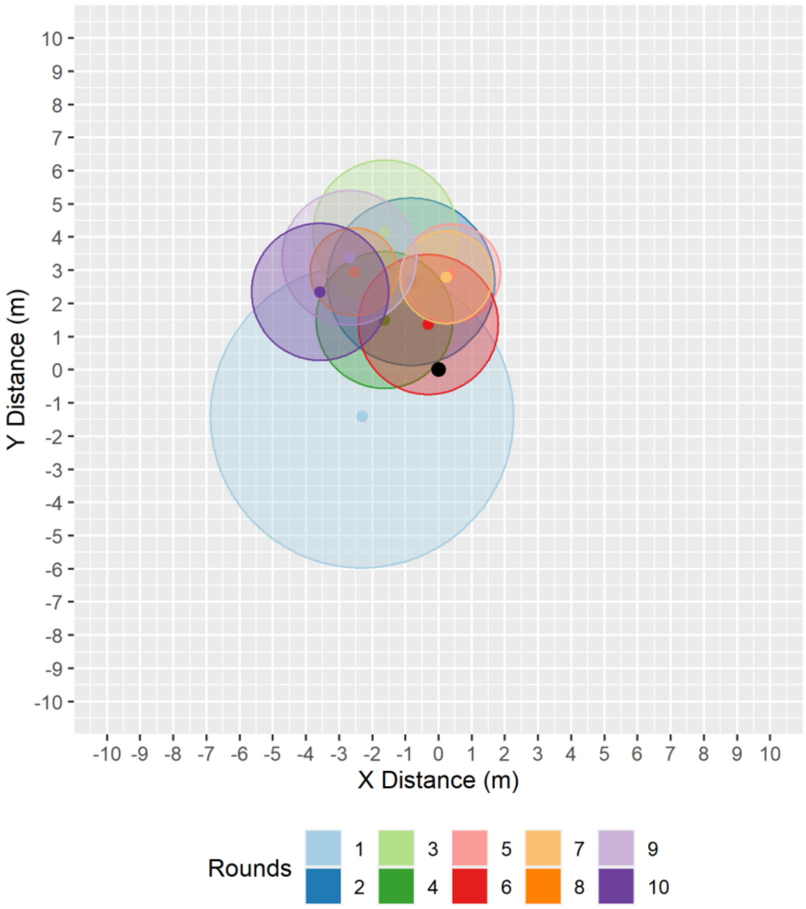


Figure 3.15: Location+WiFi condition: the true location represented by the black circle; Accuracy Error represented by solid circles; Precision Error I represented by concentric circles of the same colour.

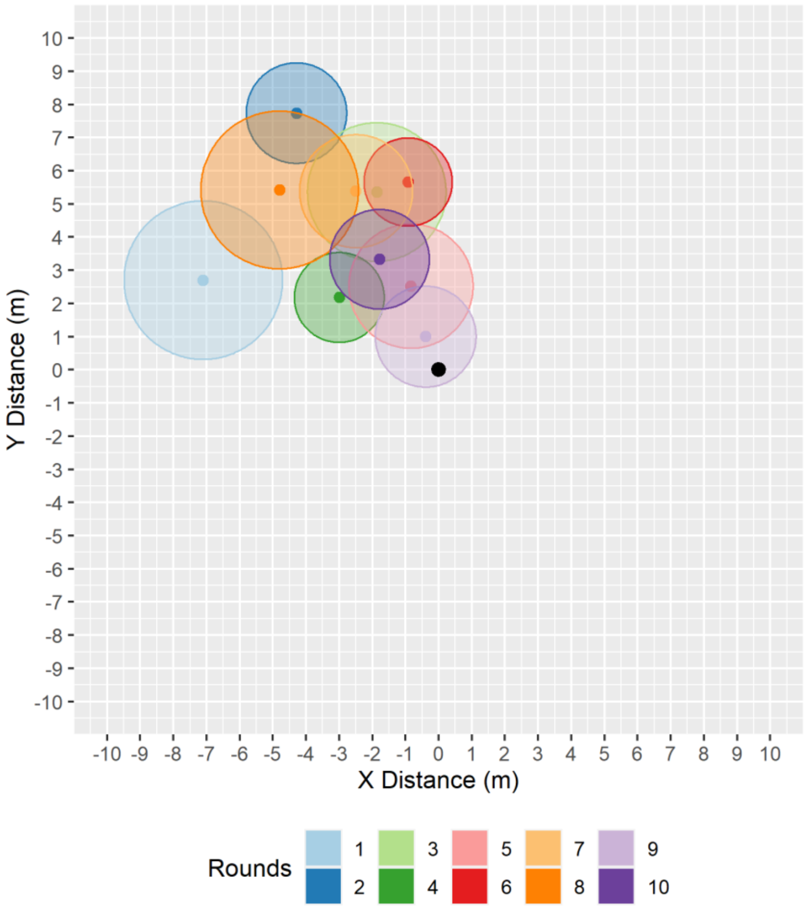


Figure 3.16: Location+MobileData condition: the true location represented by the black circle; Accuracy Error represented by solid circles; Precision Error I represented by concentric circles of the same colour.

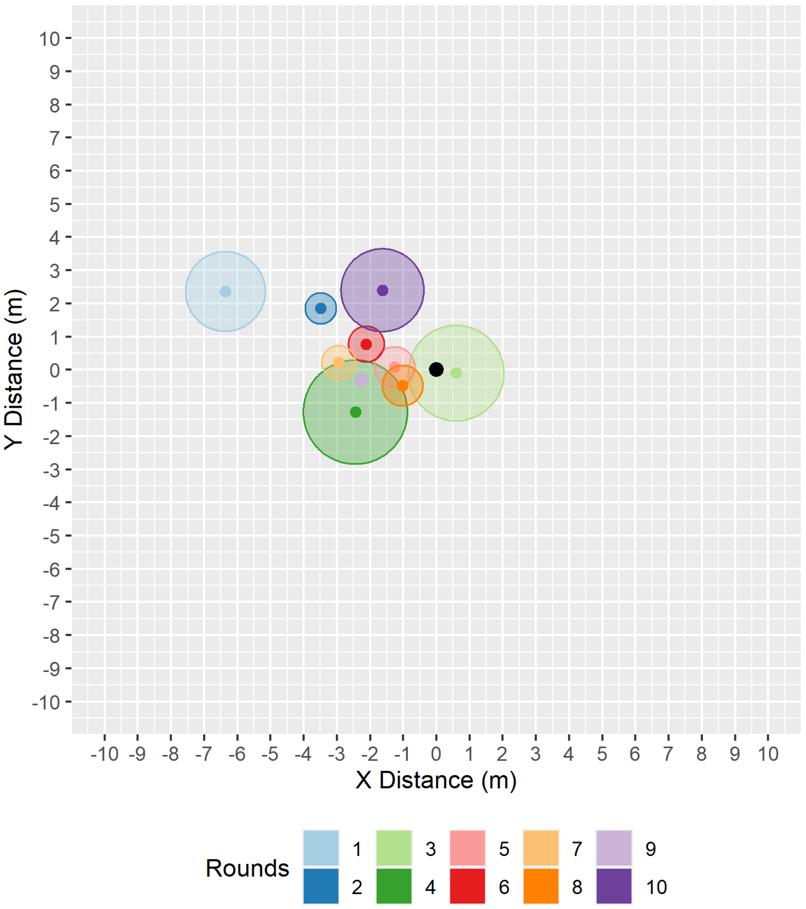


Figure 3.17: Location+AirplaneMode condition: the true location represented by the black circle; Accuracy Error represented by solid circles; Precision Error I represented by concentric circles of the same colour.

3.2.4 Precision Error II

An additional analysis was conducted to calculate precision error on subsets of location measurements from each round. This measure is referred to as Precision Error II in the chapter. To calculate this measure, the thirty location measurements from each round were divided into two datasets of 15-15 measurements. The first fifteen location measurements were counted as the first subset of location data and these measurements were regarded as being taken as part of the stabilization period where the device was kept stationary at the true location to get an accurate location fix before gathering location data for each round of an experimental condition. The next fifteen location measurements were assigned to the second subset.

The error values for each round were computed as the mean of the distances between each of the fifteen location measurements from the second subset and the mean of first subset. The mean of the error values from all the rounds of an experimental condition provides the precision error for that condition, and the mean of the error values from the condition across all twelve days provides overall Precision Error II for the condition during the experiment.

Table 3.3 shows the Precision Error II values for all four experimental conditions on all the twelve days of data collection and the last row of the table shows the overall Precision Error II for each experimental condition.

The Precision Error II results are comparable to the Precision Error I results reported in Table 3.2. The *Location+AirplaneMode* condition had the lowest variance for Precision Error II across all twelve days, with an overall lowest variance of 1.62 metres. The *Location+WiFi* condition had the second lowest variance overall, measuring 2.53 metres, and showed higher precision on nine days compared to the precision computed for the other two experimental conditions.

However, there is greater variance in the Precision Error II values for the four experimental conditions than in the Precision Error I values. This indicates that no experimental condition saw an improvement in precision as a result of dividing location data into two subsets and analysing precision error from the second half of the measurements from each round. The results indicate that the stabilization period, when the first fifteen location measurements were gathered, did not improve precision in any of the experimental conditions.

Day	LocationOnly	Location+WiFi	Location+MobileData	Location+AirplaneMode
1	3.0618	2.7689	3.0982	1.8172
2	2.3705	3.8208	3.2708	1.4755
3	2.1663	2.4245	2.3925	1.1370
4	2.3343	3.5202	3.1596	1.9437
5	2.6003	2.3479	2.5186	2.0298
6	3.1402	2.4991	2.7162	1.5106
7	3.3281	3.1808	3.1087	2.4357
8	2.8317	2.1161	2.9610	1.4959
9	3.4546	2.1661	2.5176	1.2210
10	2.5031	1.7807	2.4581	1.7614
11	1.8268	1.6395	2.7511	1.2818
12	2.3001	2.1324	2.7981	1.3851
Mean	2.6598	2.5331	2.8125	1.6246

Table 3.3: Precision Error II in all four experimental conditions across the twelve days.

Figure 3.18 presents Precision Error II statistics for all four experimental conditions from one of the testing days' data. Each line denotes the calculated Precision Error II values for all ten rounds of each condition. Figures 3.19-3.22 illustrate the Accuracy Error and Precision Error II data for each of the four experimental conditions individually. The true location is denoted by the black solid circle at the centre of the charts. The Accuracy Error for each round is represented by a solid circle, with concentric circles of the same colour representing 95% of the data. These concentric circles represent two standard deviations of the Precision Error II values for each round of an experimental condition.

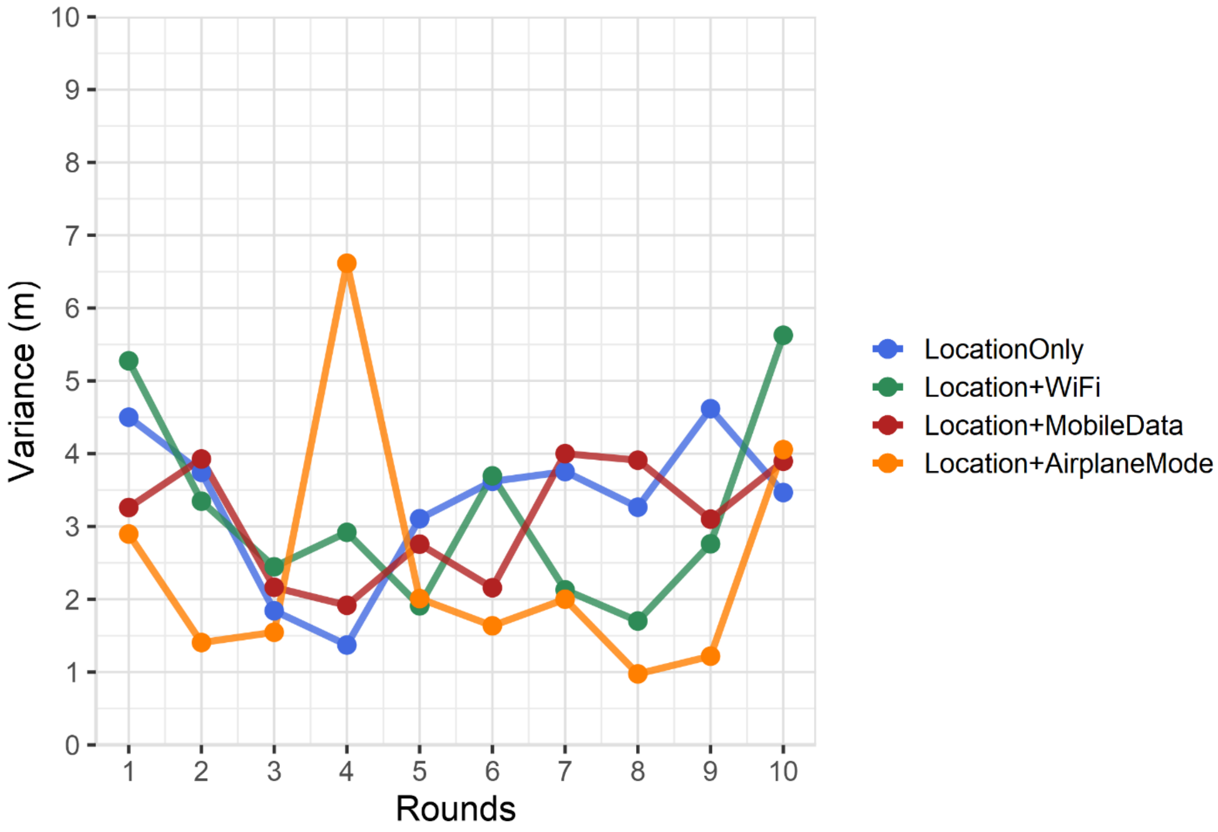


Figure 3.18: Precision Error II across the ten rounds in each experimental condition.

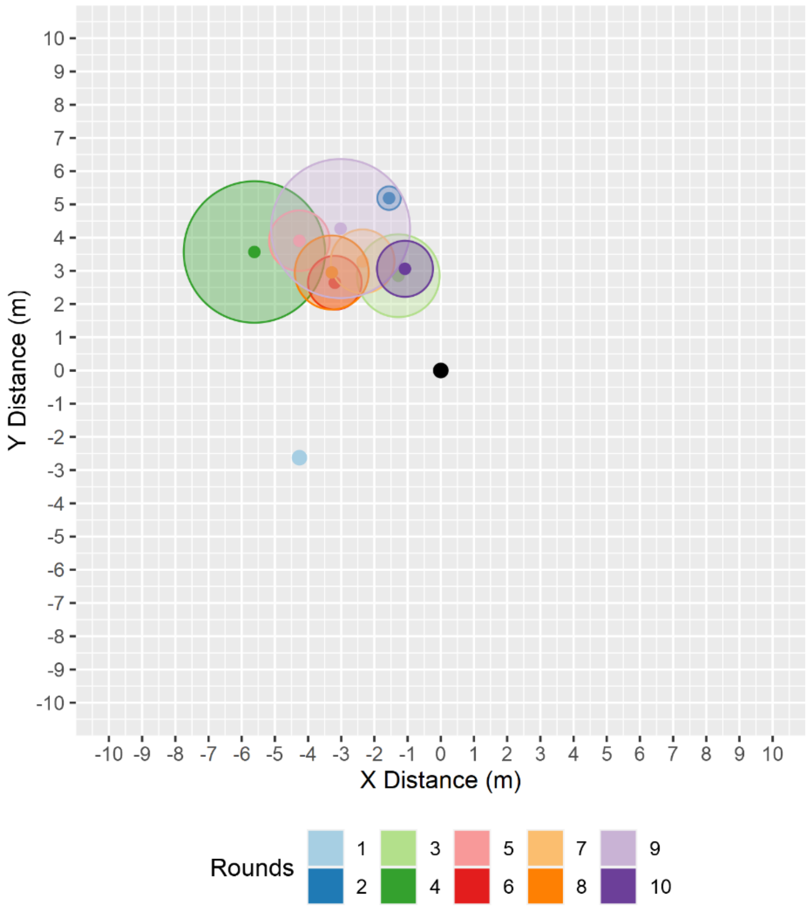


Figure 3.19: LocationOnly condition: the true location represented by the black circle; Accuracy Error represented by solid circles; Precision Error II represented by concentric circles of the same colour. Precision Error II circles not visible for rounds with high precision.

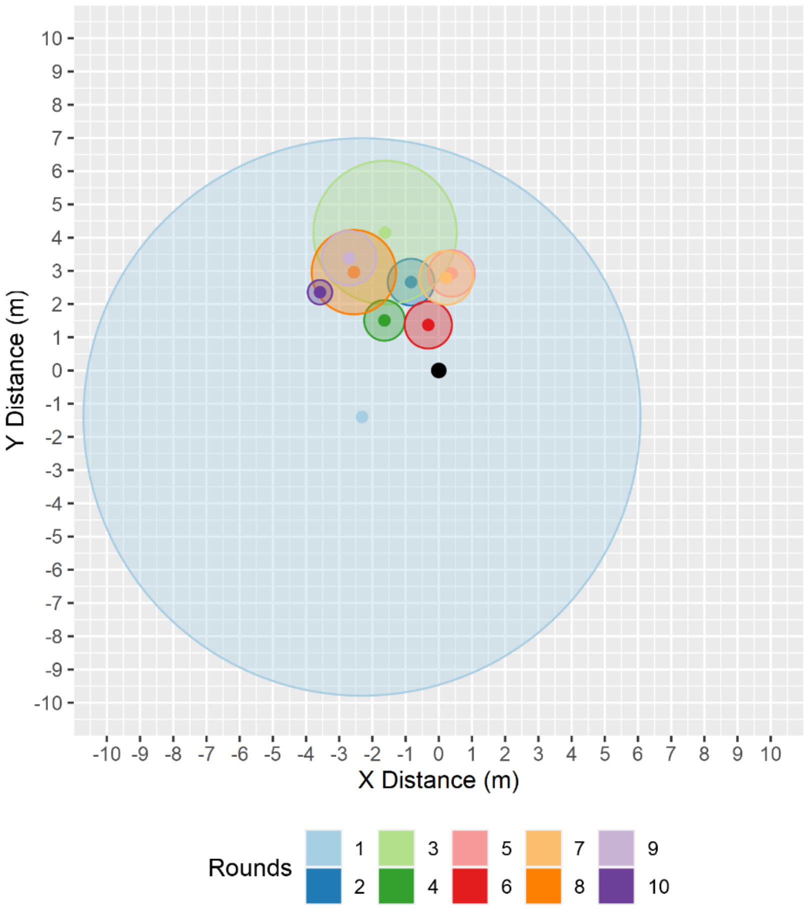


Figure 3.20: Location+WiFi condition: the true location represented by the black circle; Accuracy Error represented by solid circles; Precision Error II represented by concentric circles of the same colour.

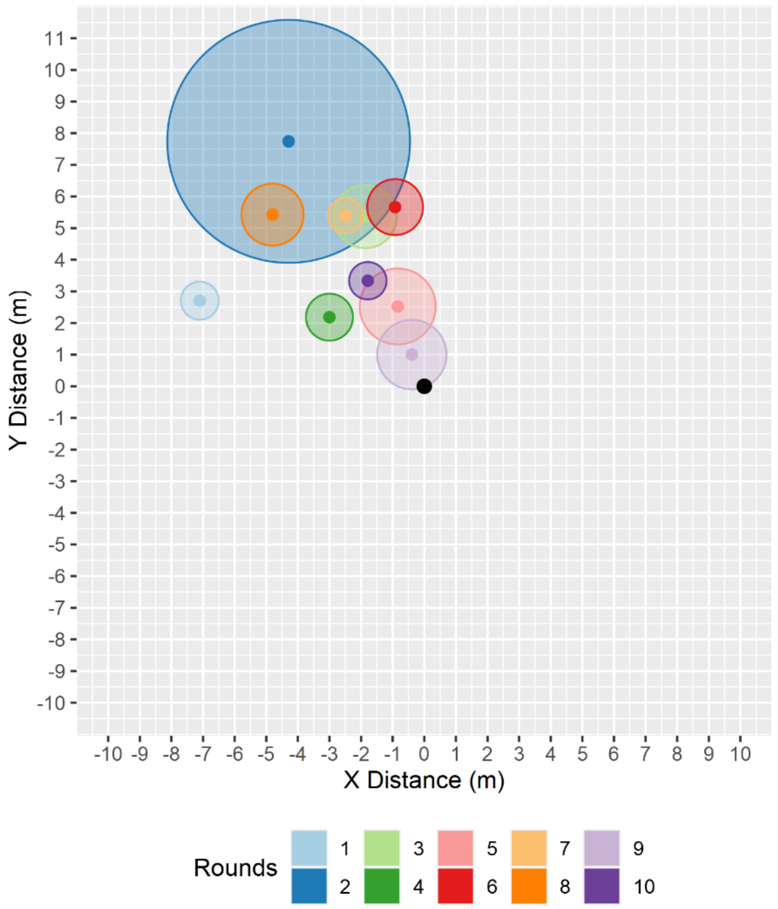


Figure 3.21: Location+MobileData condition: the true location represented by the black circle; Accuracy Error represented by solid circles; Precision Error II represented by concentric circles of the same colour.

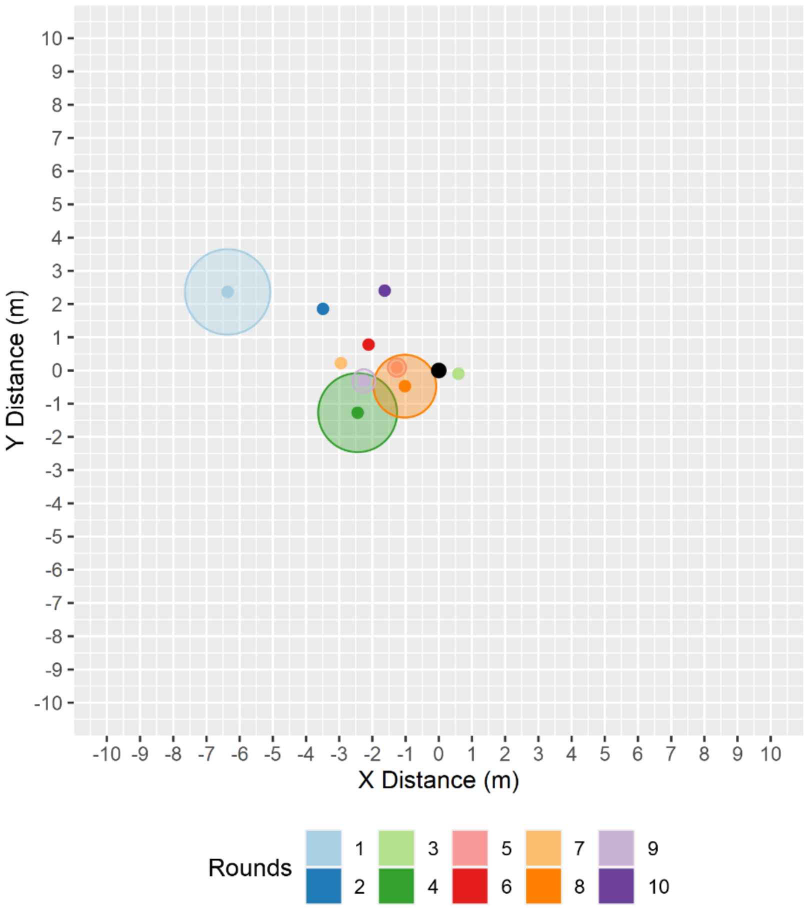


Figure 3.22: Location+AirplaneMode condition: the true location represented by the black circle; Accuracy Error represented by solid circles; Precision Error II represented by concentric circles of the same colour. Precision Error II circles not visible for rounds with high precision.

3.2.5 Effect of Experimental Conditions on Accuracy and Precision

The effect size for significant repeated measures analysis of variance (RM-ANOVA) are reported as generalized eta-squared η^2, with values <.01 considered small, approximately .06 considered medium, and >.14 considered large [17]. The post-hoc pairwise t-tests are corrected by the Holm adjustment method. No data was removed from the analysis.

RM-ANOVA showed a significant effect of experimental conditions (four different device settings) on all three dependent measures: Accuracy Error ($F_{3,33}$= 4.67, $p < .005$, $\eta^2 = 0.15$); Precision Error I ($F_{3,33} = 44.49$, $p < .0001$, $\eta^2 = 0.70$), with the effect size indicating 70% of the variance caused by the experimental conditions; and Precision Error II ($F_{3,33} = 20.88$, $p < .0001$, $\eta^2 = 0.50$) with the effect size indicating 50% of the variance caused by the experimental conditions.

The results of the post-hoc pairwise t-tests showed significant differences between the *Location+AirplaneMode* condition and each of the other three experimental conditions for Precision Error I and Precision Error II (all $p < .0001$).

3.2.6 Exploratory Analysis

During the data analysis process, notable improvements in accuracy were observed around the twentieth location measurement for approximately half of the rounds across all experimental conditions, excluding the *Location+AirplaneMode* condition. This observation prompted an exploratory analysis of the Precision Error II measure, involving adjustments to the sample sizes of the two location data subsets. The objective was to investigate how precision improved after the twentieth location measurement by segmenting each round's location data into two datasets: one comprising 20 location measurements and the other comprising 10 location measurements.

In this analysis, the error values were computed as the mean of the distances between each of the twenty location measurements from the second subset and the mean of first subset. The mean of the error values of all the rounds of a condition provided the precision error for that condition. Furthermore, the mean of the error values for each condition across all twelve days provided the overall Precision Error II for that condition during the experiment.

Table 3.4 shows the Precision Error II values across the twelve days for all the experimental conditions. The last row of the table represents the overall Precision Error II for each of the experimental conditions. The results consistently highlight the experimental condition that achieved the highest precision. Despite the reduced error values computed from modified datasets with 20 and 10 location measurements per round compared to the 15-location measurements datasets (as detailed in Section 3.2.4), there is no significant improvement in precision over the findings for Precision Error I (as discussed in Section 3.2.3).

In terms of precision across all days, the Location+AirplaneMode condition consistently showed the lowest variance, measuring an overall variance of 1.41 metres, followed by the Location+WiFi condition with the second lowest variance of 2.40 metres.

Figure 3.23 presents Precision Error II statistics for all four experimental conditions based on the modified datasets described above. Each line represents the calculated Precision Error II values for each of the ten rounds of each experimental condition.

Figures 3.24-3.27 illustrate the Accuracy Error and Precision Error II data for each of the four conditions individually. The true location is denoted by the black solid circle at the centre of the charts. The Accuracy Error for each round is represented by a solid circle, with concentric circles of the same colour representing 95% of the data. These circles represent two standard deviations of the Precision Error II values for each of the ten rounds.

Day	LocationOnly	Location+WiFi	Location+MobileData	Location+AirplaneMode
1	2.6366	2.2563	2.7317	1.5405
2	2.1641	3.8389	3.0870	1.2814
3	1.8517	1.9178	2.3287	1.0032
4	1.8412	3.4750	2.5961	1.6842
5	2.7182	2.2610	2.2643	1.8426
6	3.3809	2.6913	2.2889	1.4218
7	3.4832	3.1761	3.0725	1.9693
8	2.8230	2.2165	2.5824	1.2897
9	3.1838	1.9535	2.2272	1.1522
10	2.5310	1.5827	2.1791	1.4342
11	1.4373	1.3340	2.4445	1.1237
12	2.3178	2.0501	2.5437	1.1405
Mean	2.5307	2.3961	2.5288	1.4069

Table 3.4: Precision Error II (modified subsets) in all four experimental conditions across the twelve days.

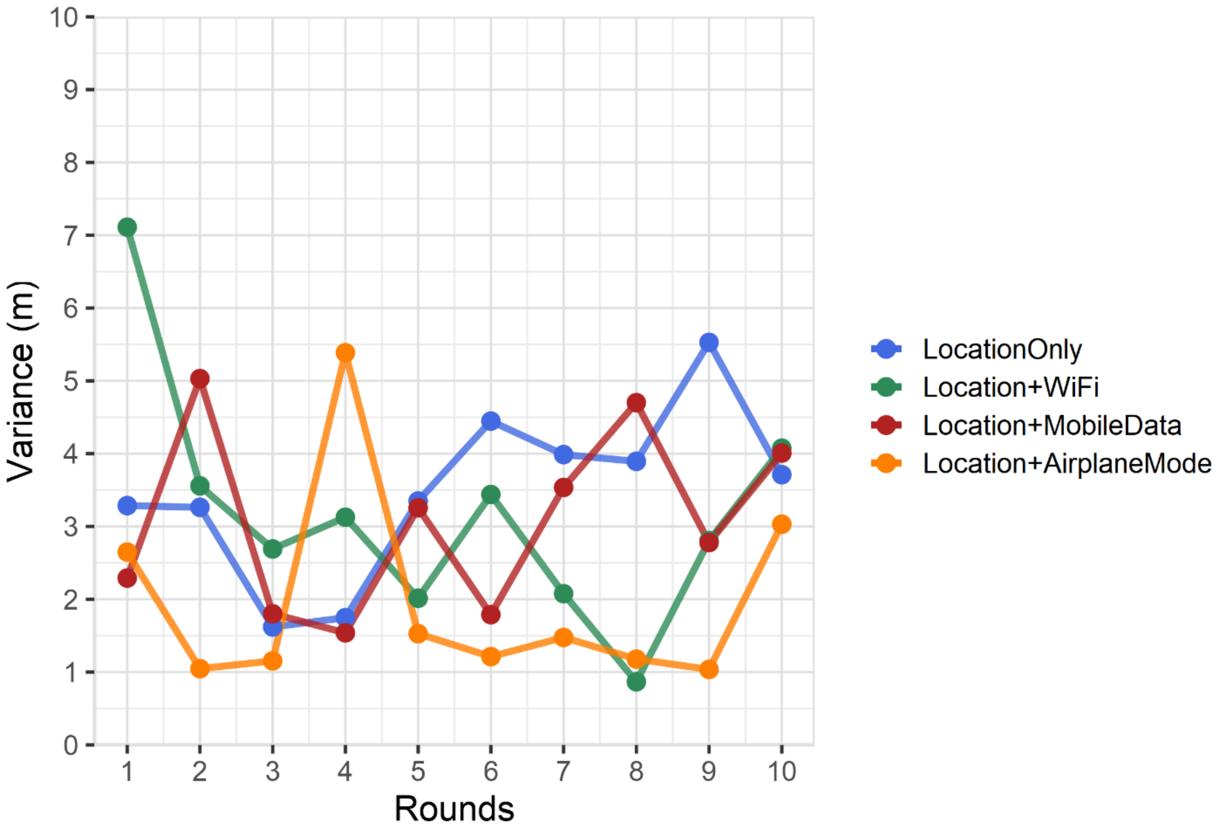


Figure 3.23: Precision Error II (modified subsets) across the ten rounds in each experimental condition.

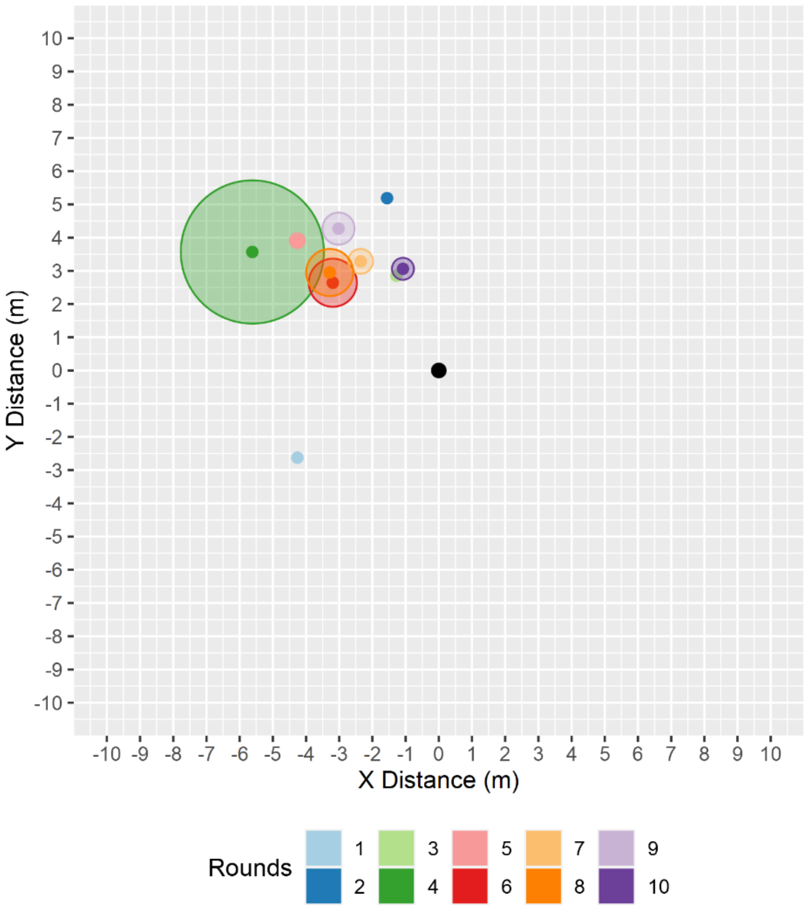


Figure 3.24: LocationOnly condition: the true location represented by the black circle; Accuracy Error represented by solid circles; Precision Error II represented by concentric circles of the same colour. Precision Error II circles not visible for rounds with high precision.

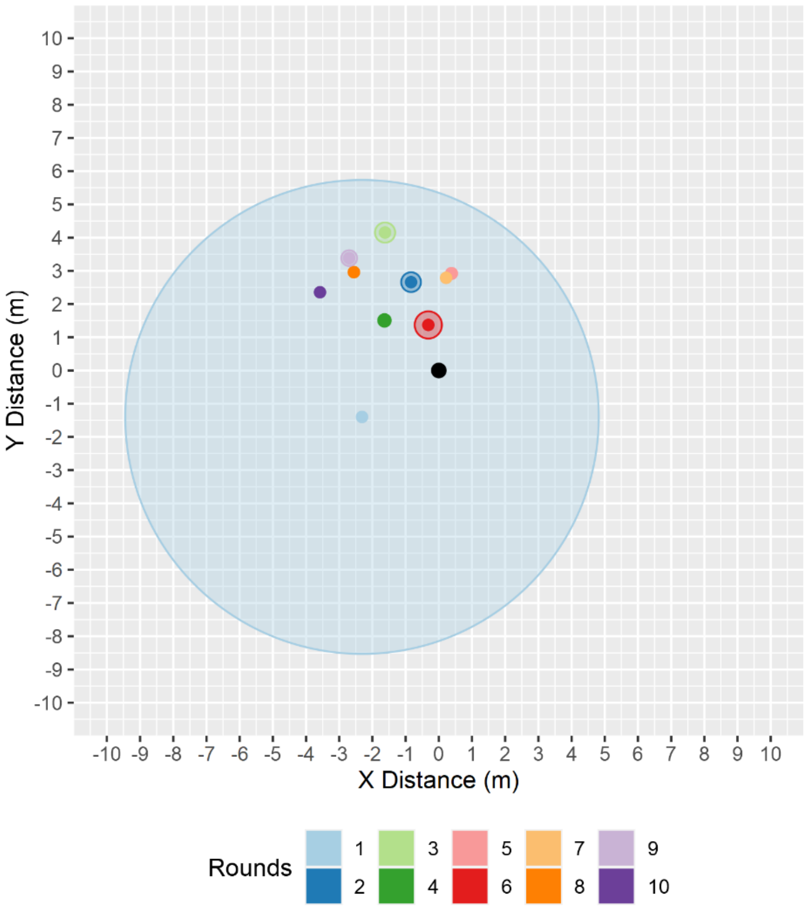


Figure 3.25: Location+WiFi condition: the true location represented by the black circle; Accuracy Error represented by solid circles; Precision Error II represented by concentric circles of the same colour. Precision Error II circles not visible for rounds with high precision.

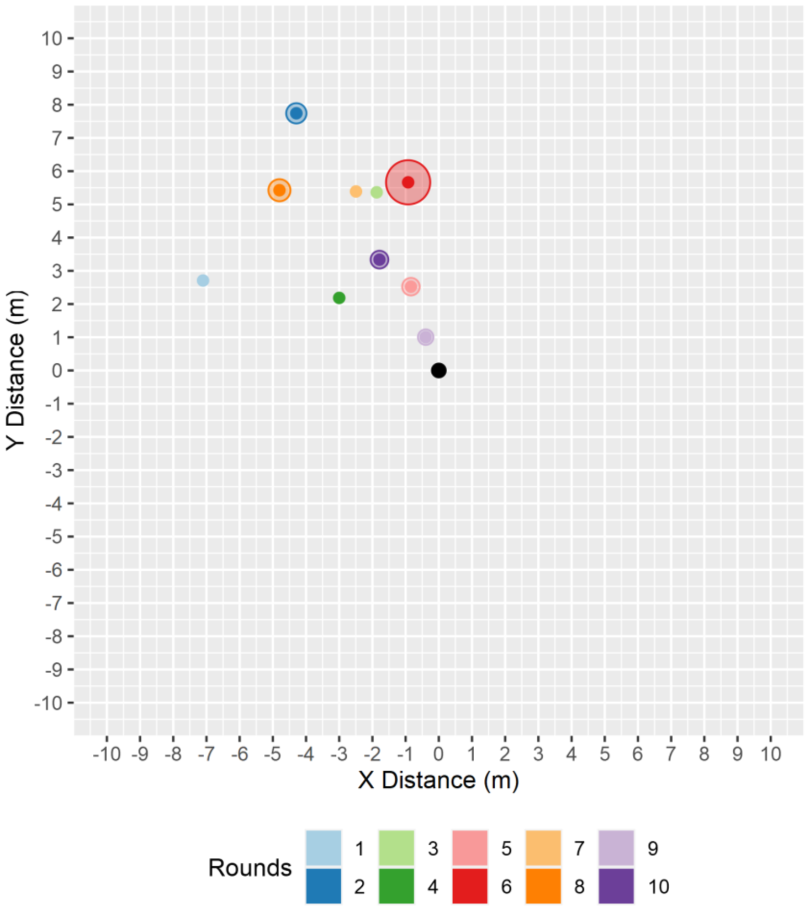


Figure 3.26: Location+MobileData condition: the true location represented by the black circle; Accuracy Error represented by solid circles; Precision Error II represented by concentric circles of the same colour. Precision Error II circles not visible for rounds with high precision.

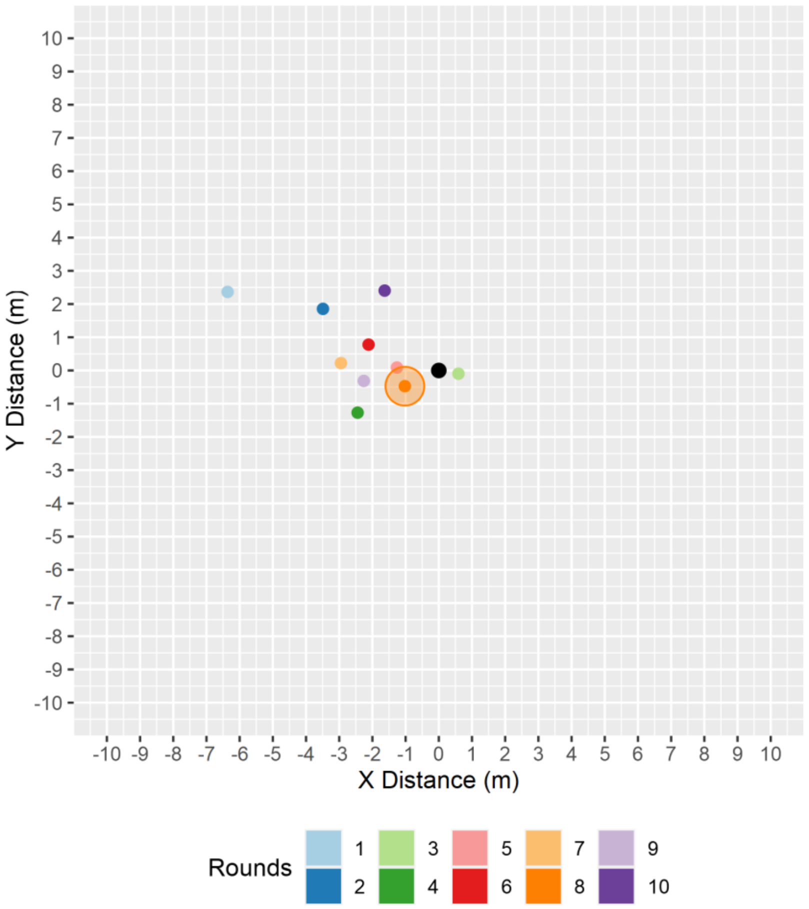


Figure 3.27: Location+AirplaneMode condition: the true location represented by the black circle; Accuracy Error represented by solid circles; Precision Error II represented by concentric circles of the same colour. Precision Error II circles not visible for rounds with high precision.

The results of the exploratory analysis demonstrated that precision was not significantly impacted by changes in the sample size of datasets. A t-test shows that the difference observed between Precision Error II values in Sections 3.2.4 and 3.2.6 is not statistically significant ($p = .1736$).

The initial hypothesis suggested a potential reduction in precision error with modified datasets. However, the observed improvement in precision was not consistent across all rounds and days for any of the experimental conditions. The findings from Precision Error I highlight enhanced precision by utilising a larger dataset, as demonstrated by the analysis with 30 location measurements per round. For Precision Error II analysis, employing a larger dataset with a minimum of 30 location measurements in each subset would be crucial in conducting a comprehensive evaluation of the improvements in the precision of location data.

3.3 EFFECT OF SKY COVER CONDITIONS ON THE RESULTS

GPS data is affected by weather conditions and readings are the most accurate when there is a clear view of the sky [86]. The weather data was logged as part of the quantitative measures recorded during the study. Table 3.5 shows the sky cover conditions during the twelve days of the experiment.

Day	Sky Cover
1	Few clouds
2	Light snow
3	Light snow
4	Clear sky
5	Clear sky
6	Broken clouds
7	Broken clouds
8	Clear sky
9	Broken clouds
10	Broken clouds
11	Few clouds
12	Few clouds

Table 3.5: Sky cover conditions across the twelve days of the experiment.

Detailed information is presented in Table 3.6, which displays the sky cover conditions that were present when the location data with the highest and lowest accuracy and precision was gathered across the four experimental conditions.

		LocationOnly	Location+WiFi	Location+MobileData	Location+AirplaneMode
Accuracy	Highest	11	7	4	11
	Lowest	6	6	6	9
Precision I	Highest	11	11	3	3
	Lowest	7	2	7	7
Precision II	Highest	11	11	3	3
	Lowest	9	2	2	7

Table 3.6: The day corresponding to the categorical sky cover condition with the highest and lowest location accuracy and precision across the four experimental conditions.

The sky cover conditions observed for each day in all four experimental conditions were obtained by analysing the location data for all days (Table 3.5). Next, the highest and lowest values for Accuracy, Precision I, and Precision II (corresponding to Accuracy Error, Precision Error I, and Precision Error II, respectively) were identified across all days and experimental conditions. Subsequently, the day numbers corresponding to the categorical sky cover conditions were assigned to the highest and lowest values of the dependent variables (Table 3.6).

Four sky cover conditions were recorded during the study: *clear sky, few clouds, light snow, and broken clouds*. Broken clouds appeared to be the main cause of the lowest accuracy and precision in location data across all four experimental conditions. This is because broken clouds can scatter radio waves, making it difficult for devices to determine their location accurately. In contrast, the highest location accuracy and precision were observed when there were few clouds or light snow in addition to the clear sky condition.

3.4 INTERPRETATION OF THE RESULTS

The goal of Study 1 was to determine the accuracy and precision of GPS data received on a smartphone under different device settings conditions.

The results of the study revealed that the location data in the *Location+AirplaneMode* condition had significantly higher accuracy and precision than the other three experimental conditions. The results from this condition were expected to be similar to the results from the *LocationOnly* condition due to the fact that only device location service was enabled in both cases and the device did not have access to Wi-Fi or cellular networks. However, the analysis of the results showed that airplane mode had a significant effect on both accuracy and precision of location data. Airplane mode eliminates all signal interruptions from Wi-Fi, Bluetooth, and cellular towers that can interfere with GPS signals. Therefore, GPS data recorded under the *Location+AirplaneMode* condition had higher accuracy and precision than the *LocationOnly* condition. These results suggest that mobile map applications can be used without network connectivity with an accuracy radius of up to approximately 4 metres.

The results from the study show that mobile map applications can be used without network connectivity and this information can be useful for map and navigation applications that need to be used in areas where there is no network connectivity. The results from the analysis of weather data can be used to determine the best sky cover condition for navigation and location tracking services. This information could also be used to design studies on the effects of sky cover conditions on location data.

CHAPTER 4

STUDY 2: USER EXPERIENCE OF DIFFERENT LEVELS OF GPS ACCURACY

The goal of Study 2 was to investigate the level of location accuracy required to use mobile map applications in order to correctly identify test plots in an agricultural field research scenario. The study also investigated various strategies employed by the participants in completing the location-finding tasks at different accuracy levels. Study 1 determined the accuracy and precision of GPS data received on a smartphone and the amount of error that affects the user's location on the map. The plots in an agricultural field are closely grouped together, requiring metre-level location accuracy for carrying out tasks of correctly finding the locations of test plots. To achieve the level of accuracy required for the plot identification tasks of Study 2, the Wizard of Oz [19] method was used to simulate GPS for displaying location on the custom mobile application's map interface. An outdoor study was designed with location-finding tasks equally distributed across different accuracy level conditions with increasing levels of error rate in the location of the location marker. The study aimed to identify the accuracy level that is sufficient for successfully carrying out location-finding tasks in the agricultural field research scenario.

4.1 RESEARCH METHODS

The following section describes the study system, experimental conditions, study tasks, procedure, participants' demographics information, and study design.

4.1.1 Study System

A custom Android application was developed in Flutter with two interface modes: *server* and *client*. The application was deployed on two Android smartphones with one of the two interface modes enabled on each smartphone. Participants were provided with the smartphone with the client-mode application interface for performing the tasks during the study. The experimenter operated the server-mode interface of the application to perform GPS simulation, adjust accuracy levels settings, select task plots, and save study session data. The GPS simulation entailed tapping on map locations on the server side of the application, which resulted in displaying the current location of the user on the client side of the application. The smartphones' GPS service was disabled for the duration of the study, and the only location information available to the participants during the study was relayed from the server application with GPS simulation when the experimenter tapped on the screen to update the user's current location as they moved. Figure 4.1 shows the two interface modes of the application. A third-party screen recording application was used on both participant and experimenter smartphones. During data analysis, recordings from both phones were synchronized for playback and analysed to examine participants' interactions with the map application concerning blue dot's location information and GPS simulation, providing valuable insights for the study. Task completion times were also determined by analysing the synchronized videos.

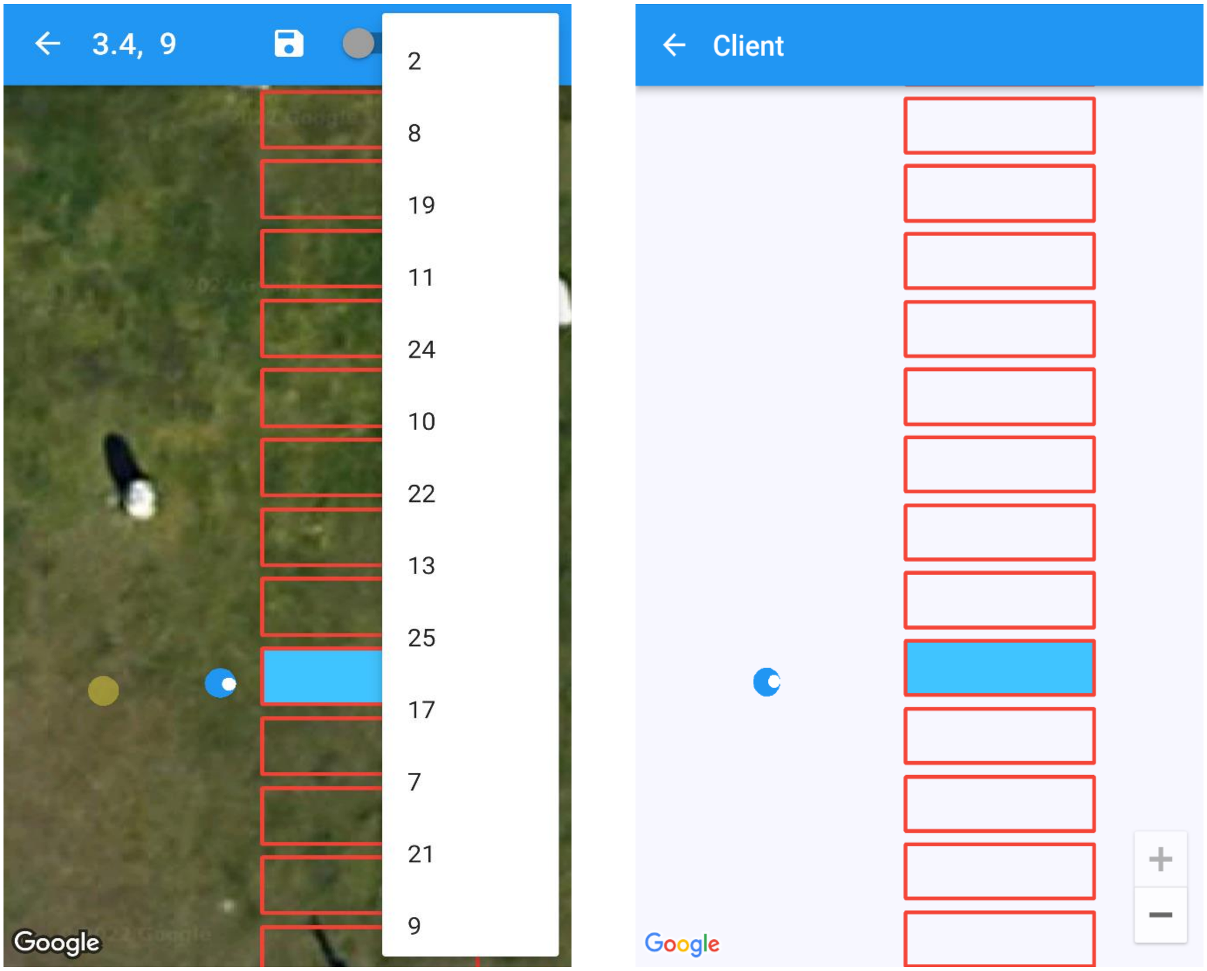


Figure 4.1: Server-mode application interface (left) and client-mode application interface (right).

4.1.1.1 Overview

An overlay of a column of rectangular regions that resembled plots in an agricultural field was drawn over Google Maps which was displayed in both of the application modes. A blue dot was displayed on the map that represented participants' current location in the field. A white circle inside the blue dot represented the direction in which the participants held the smartphone while performing the tasks. A yellow dot visible on the server screen reflected the location of the blue moving dot on the client screen. This interface element helped in comprehending participants' perceptions of the blue dot's accuracy during the tasks, thus providing the opportunity to ask follow-up questions and understand their reasoning behind the ratings provided in the subjective questionnaire completed after each task.

The two interface modes differed in two ways in terms of map representation: the map type and number of plots in the plot column. This decision was driven by the findings from the pilot and pre-study (see Sections 4.7 and 4.8). In the server mode, satellite view of the maps was used; in the client mode, terrain view was used. The number of plots visible in the server mode was thirty, which was the same as the number of plot markings made on the ground. On the other hand, plots were extended in number from both ends of the column by five, making a total of forty plots visible on the client-mode map application interface.

4.1.1.2 Application Interface Modes

- *Server:* The experimenter operated the application in the server mode to simulate GPS on the client-mode application interface using the Wizard of Oz method. Figure 4.1: left depicts the application interface in the server mode, which includes options for managing the application's settings. The app bar indicating the current error rate and plot selection and a drop-down list of plot numbers were only displayed on the server-mode application interface. The experimenter would select a plot from the list, and the plot would be highlighted in blue on both interface modes. Figure 4.1 shows plot number 9 highlighted on both screens, and the app bar on the server-mode application interface displays the error rate (in metres) and the plot currently selected for the task.

- *Client:* The smartphone with the application in client mode was provided to the participants for completing the study tasks. In this mode, participants could perform various gestures such as panning and zooming the map area and rotating the map view. Depending on the experimental condition selected on the server, the blue dot on the client screen was offset to an error amount corresponding to the accuracy level associated with that condition. Figure 4.1: right shows the blue dot at the location where the yellow dot shows on the server screen. This indicates the addition of an error amount of 3.40 metres (displayed on the app bar in Figure 4.1: left) to the true location of the blue dot visible on the server screen.

4.1.2 Experimental Conditions

The study consisted of six accuracy levels with increasing degrees of error added to the true location of the blue dot displayed on the server-mode application interface. As a result, the blue dot showed at a different location on the client-mode application interface. In addition to the error amount, the blue dot on the client-mode application interface was displayed at a random angle between 0° and 360°. With each tap on the server screen's map, a new random angle value was selected from the range and the blue dot was displayed in a direction different from the previous one. The blue dot's location on the server-mode application interface is referred to as the true location—the location point on the map where tap gesture was performed to update the user location displayed on the client-mode application interface.

Participants were informed about the change in accuracy levels prior to the start of a condition and that their location on the map may or may not be accurate.

The six different accuracy levels are:

- *0.0 metres:* In the first accuracy level, no error was added to the true location of the blue dot displayed on the client-mode application interface.

- *0.85 metres:* An error of 0.85 metres was added to the true location. In this case, the blue dot was displayed 0.85 metres away from its true location in a random direction on the client-mode application interface. This error amount was equal to half the length of the edge of the plots that were marked on the ground.

- *1.70 metres*: An error of 1.70 metres was added, and the blue dot was shown at a random angle from the true location. This error amount was the same as the length of the edge of each plot.

- *2.55 metres*: The fourth accuracy level requirement raised the error amount added to the blue dot's location by incrementing the previous error amount by 0.85 metres.

- *2.975 metres*: This accuracy level was an intermediate level between *2.55 metres* and *3.40 metres*. It was calculated as the average of the two accuracy levels.

- *3.40 metres*: The last accuracy level had the highest amount of error added as an offset to the true location and was calculated by adding the increment amount of 0.85 metres to the fourth accuracy level error amount.

In all accuracy level conditions except the first, the blue dot on the client map was offset by an error amount with each tap that updated participants' location to reflect their movements on the field. With every tap, the direction in which the blue dot was displayed with respect to the true location also changed.

Figure 4.2 shows a participant interacting with the map application (in client mode) during a study task. Figure 4.3 shows the plot markings on the ground, with two single-coloured flag stakes marking each plot edge. The research presented in this thesis was part of a larger project with the collaborators in the College of Agriculture. The plot size for the study tasks was determined by the standard size used by those collaborators in their fieldwork research and experiments.

Figure 4.2: A participant standing in front of a plot edge performing a task during the study. Plot markings with light-yellow coloured flags visible on the ground.

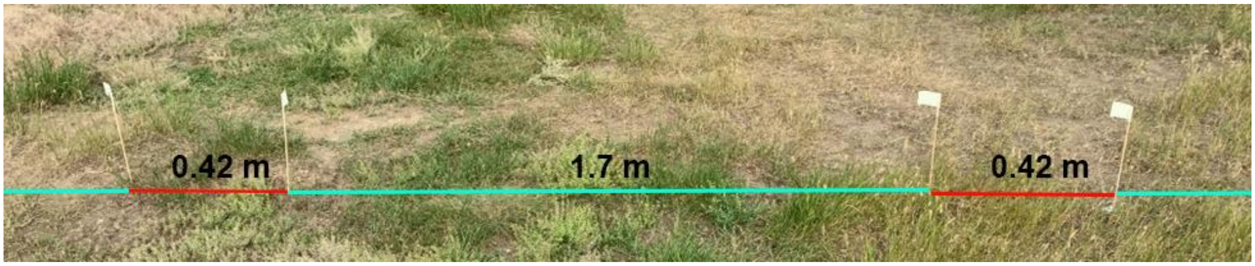


Figure 4.3: Annotated close-up of the plot markings: the length of the plot edge (1.7 metres) is depicted by the green lines, and the distance between two plots (0.42 metres) is depicted by the red lines.

4.1.3 Study Task

For each task of the study, a target plot was selected from the list of plot numbers on the server-mode application interface (see Figure 4.1: left), resulting in highlighting the corresponding plot in blue on the plots column on the maps of both the server and client devices. Participants were asked to locate the highlighted plot on the ground by using the blue dot's movements on the map that represented their real-world movements on the field. They were instructed to walk along the marked edges of the plots on the ground while performing the tasks. When they saw a plot highlighted on their screen, they were asked to ascertain where on the plots column a plot was highlighted, their location with respect to that plot highlight, and the direction to move in order to locate the highlighted plot on the ground. The pan, zoom, and rotate controls on the map were available for the participants to use at their discretion. They were informed of the change in accuracy level with each new experimental condition. There were two tasks assigned to each condition, and each task was required to be completed in a maximum of two attempts. There was no time limit for completing a task as the goal was to see if participants were able to find a plot without imposing a time limit. They were asked to stand in front of the edge of the plot that they identified as the highlighted target plot and inform the experimenter of their choice. After completing the task, they were asked to provide rating responses to four subjective questions that measured their use of, trust in, perceived accuracy of, and usefulness of the blue dot during the entire duration of the task. Each participant performed twelve tasks in total, with two tasks per accuracy level.

4.1.4 Procedure

Participants were asked to complete a pre-study demographics questionnaire regarding their familiarity with map-based mobile applications and their use of these applications. They completed an informed consent form before the study and then were given information about the study and their role as a participant. They were provided with an Android smartphone with the study application running in the client mode. They were given a detailed demonstration about the application interface elements and how to perform the tasks:

- Meaning and use of the blue dot
- White dot enclosed within the blue dot
- Column of plots and their flag markings on the ground with respect to the on-screen column layout
- Cardinal directions of the marked plots on the ground
- Changes in the location and direction of the blue dot with respect to their directional orientation and movements on the ground
- Navigating the field while completing the tasks
- Completing a task and positioning themselves after identifying the highlighted plot

Following the instructions, participants completed a demonstration task to familiarize themselves with the process of performing and completing a task. The participants then carried out twelve tasks in six experimental conditions under six different accuracy levels. After completing each task, the participants completed a set of rating scale questions in order to assess the blue dot's use, trustworthiness, perceived accuracy, and usefulness during the task. After each condition, they completed the NASA Task Load Index (NASA-TLX) questionnaire [38] to report their overall effort and frustration with the system along with the physical, mental, and temporal demands they felt while completing the tasks in each condition. At the end of the study, participants were asked to provide subjective responses to report their strategies for locating plots during the tasks.

4.1.5 Study Design

The study addressed the following research questions:

- RQ1: What is the effect of reduced location accuracy on the user task of location finding?
- RQ2: What is the user experience of different levels of location accuracy?
- RQ3: What strategies do users employ to navigate situations of insufficient location accuracy?

The within-subjects study used a repeated-measures design with accuracy level as the independent variable. The dependent measures were user errors, task completion time, subjective ratings of 10-point scale questions after each trial, and NASA-TLX ratings after each experimental condition.

The success rate in the first and second attempts at completing a task was also analysed to further explore the error count for each task of the different experimental conditions. In addition, an exploratory two-factor analysis was performed with trial as the other independent variable; the dependent measures were the same for the analysis.

4.1.6 Participants

Twenty-two participants (twelve men, nine women, one non-binary) aged 18-38 years (Mean = 27, SD = 5.6) were recruited from a local university and were provided with a $12 honorarium for their participation in the study that took on average 60 minutes to complete.

People with a wide variety of backgrounds need to find plots in the agricultural research fields, and often, the people doing the work in the field are summer student employees. Therefore, the participants recruited for the study were university students from different academic disciplines who were regular smartphone users familiar with map-based applications, matching the intended user profile.

All participants completed the demographics questionnaire prior to Study 2. The participants' reported estimated smartphone usage was 30.1 hours in an average week. Nineteen out of the total participants cited Google Maps as their main map-based app while the rest chose Apple Maps as their main map-based app. Twelve participants reported being extremely familiar with using the map app, eight moderately familiar and only two somewhat familiar.

The average of the estimated number of hours spent using their main map-based apps was 2.5 hours per week. Table 4.1 shows the number of participants who used their preferred map-based app on different devices.

Devices	Participants
Phone	22
Computer	11
Tablet	3
GPS Device	0
Smartwatch	3
Car UI	5
Other	0

Table 4.1: Number of participants using their main map-based app on different devices.

The most popular device was the phone, with 22 participants using it, followed by the computer and the car UI. The tablet, GPS device, and smartwatch were less popular, and no participants used any "other" device.

4.2 DEMOGRAPHICS DATA ANALYSIS

This section presents the findings derived from the detailed analysis of participants' responses to questions reported in Table 4.2.

The participants were asked to specify the purposes or tasks for using their main map-based application (see Question 6, Table 4.2). During data analysis, content analysis [14,83] was performed on their subjective responses to the question, revealing the four most frequently reported tasks. Seventeen participants mentioned using their main map app for navigation, eight for accessing public transit information, three for determining distance, and three for estimating travel time.

QN	Question
1	Age
2	Gender
3	How many hours per week do you spend on a smartphone (in an average week)?
4	Which map-based apps do you use regularly?
5	State the name of your main map-based app from the previous question if you selected multiple answers.
6	How do you use your main map-based app?
7	How familiar are you with the app mentioned in the previous answer? Answer based on your main map-based app.

8 How many hours per week do you use your main map-based application (in an average week)?

9 What tasks do you use the map-based app for?

A. See where I am
B. Get an overview of a new place
C. Get a route to a destination
D. Get turn-by-turn directions
E. Find locations or services in my area
F. See real-time traffic information
G. Get alerts on traffic congestion, speed limits, etc.
H. Voice guidance navigation
I. Offline map navigation
J. Find walking, hiking, skiing, or bicycle paths
K. Find the distance between places

10 If you selected "Other" in the previous question and rated it for usage, please specify what other tasks you are referring to.

11 On what device do you use your map-based app?

12 For what tasks do you use the "moving dot" that shows your location on the map? Rank in order of use - 1 being the reason for most use.

13 Please specify what tasks you use the “moving dot” for if you ranked “Other” as one of your top choices in the previous question.

14 How often have you been confused by the direction of the moving dot?

15 Give an example of a scenario where the moving dot's direction confused you.

16 Scenario 1: On a scale of 1 to 10, rate how accurate you find your location shown by the “moving dot” in the case of finding a house.

17 Scenario 1: What is the reason that you think the moving dot is accurate?

18 Scenario 1: What is the reason that you think the moving dot is inaccurate?

19 Scenario 2: On a scale of 1 to 10, rate how accurate you find your location shown by the “moving dot” in the case of finding your parking location in a parking lot.

20 Scenario 2: What is the reason that you think the moving dot is accurate?

21 Scenario 2: What is the reason that you think the moving dot is inaccurate?

22 Scenario 3: State a small-scale map-navigation example (similar to the previous question on parking location).

23 Scenario 3: Now, on a scale of 1 to 10, rate how accurate you find your location shown by the “moving dot” in the scenario 3 example stated by you.

24 Scenario 3: What is the reason that you think the moving dot is accurate?

25 Scenario 3: What is the reason that you think the moving dot is inaccurate?

Table 4.2: Demographics Questionnaire

Figure 4.4 shows participant ratings for their use of the map app for some common tasks, and the results correlate with their subjective responses to the open-ended question, Question 6.

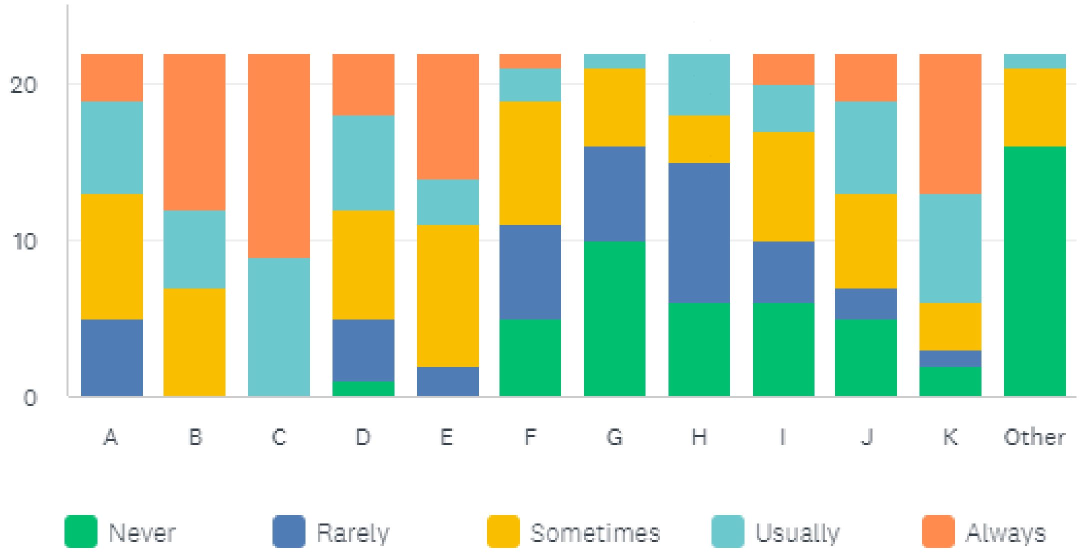


Figure 4.4: Participant ratings for use of their main map-based app for different tasks labelled from A to K (Question 9, Table 4.2).

Questions 12 to 25 focused on ascertaining the participants' perceived accuracy of the moving dot and the reasons associated with the ratings. The green bars for each task depicted in Figure 4.5 show the number of participants who ranked a task as their first choice for using the moving blue dot in the map app (Question 12).

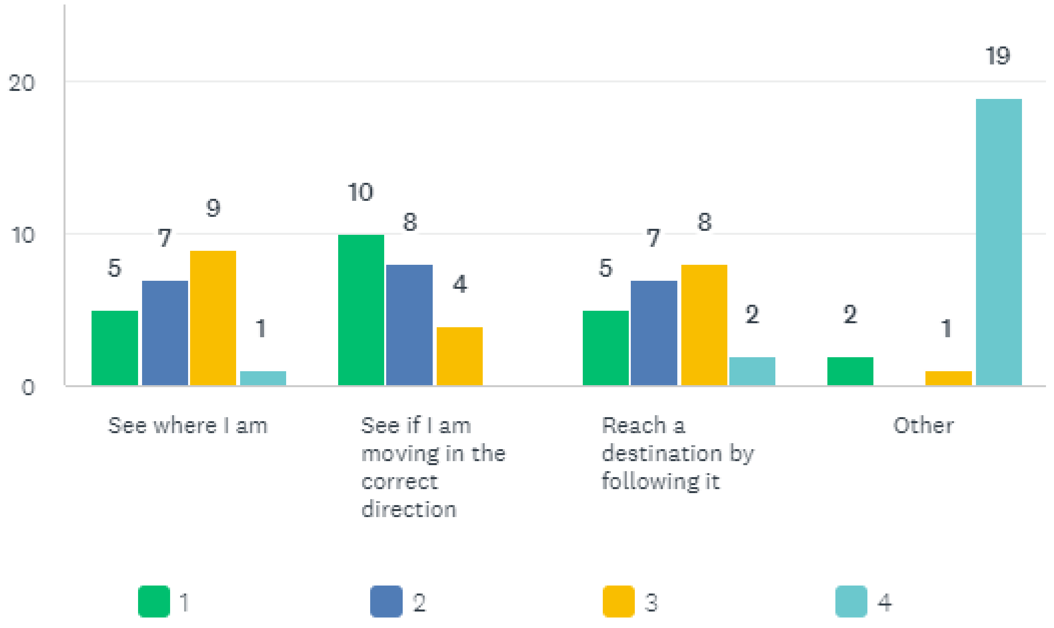


Figure 4.5: Participant rankings for use of the moving blue dot.

With respect to how often the participants had been confused by the direction of the moving dot, twelve participants answered “sometimes”, eight “rarely”, and two “never”. One participant stated, “Sometimes if I move in the dot direction, I move more farther from my destination”. Another reported an incident where “the moving dot didn’t update immediately so it showed I was facing the right direction while I was going the other way”. Two participants also commented on the accuracy of the moving dot, saying, “It is not as accurate as a dedicated GPS, so I need to walk in a direction and wait for update before confirming that my movement matches moving dot,” and that “GPS is not accurate enough so it cannot find my location”.

The participants were then asked to rate the accuracy of the moving dot in three different scenarios (see Questions 16-25, Table 4.2) using a numeric 1-10 scale, where 1 represents “not at all accurate” and 10 represents “extremely accurate”.

The three scenarios were:

- Scenario 1: Locating a house.
- Scenario 2: Finding the location of a parked vehicle in a parking lot.
- Scenario 3: Providing an example from their own map navigation experience and then rating the accuracy of the dot.

In each scenario, two follow-up questions were asked after participants provided their ratings of the location accuracy of the dot. The first question asked about the reasons for their perception of the moving dot being accurate, and the second question asked about the factors that caused the moving dot to be inaccurate.

In Table 4.3, the multiple choices of the reasons for the first follow-up question are listed along with the total number of responses collected for each choice for all three scenarios (columns 2 to 4). Table 4.4 presents the multiple choices of reasons for the participants to select from for the second follow-up question; the number of responses for each multiple choice is provided in the three columns (columns 2 to 4) of the table for each of the three scenarios.

Reason	Scenario 1 Responses	Scenario 2 Responses	Scenario 3 Responses
Shows exactly where I am	10	7	13
Helps me reach a destination correctly	16	6	12
I do not find any error in my location on the map	3	2	2
May be a little off but still accurate enough to take me to the correct location	16	8	14
Other (please specify)	0	1	0

Table 4.3: Participant responses to the first follow-up question.

Reason	Scenario 1 Responses	Scenario 2 Responses	Scenario 3 Responses
Does not reflect my location correctly on the map	5	6	3
Changes location frequently	4	1	2
Shows my location way off from the actual real-world location	5	1	5
Does not move with me	5	6	2
The direction it shows is unreliable or incorrect at times	14	7	12
Other (please specify).	1	0	1

Table 4.4: Participant responses to the second follow-up question.

4.2.1 Scenario 1

Scenario 1 required participants to rate the accuracy of the moving dot when using their main map-based app to find a house. They provided an average rating of 8 on the 10-point scale. Column *Scenario 1 Responses* in Table 3.3 shows their reasoning: despite some moving-dot location inaccuracy, their main map-based app would be able to find a house.

The second follow-up question asked them about the reason(s) for considering the moving dot's location to be inaccurate, and fourteen participants indicated that they find the direction of the moving dot to be unreliable or incorrect at times. Column *Scenario 1 Responses* of Table 4.4 presents the summary of responses to this question.

4.2.2 Scenario 2

Scenario 2 asked the participants to rate the moving dot’s location accuracy when they used their main map-based app to find their parking location in a parking lot. The questions related to Scenario 2 were optional to answer, as this scenario would not be relatable to participants who do not drive a car or similar vehicle and have not faced a situation where they had to use a map app for that purpose.

Eight participants indicated that they did not relate to the situation presented in the scenario. The average rating from the remaining fifteen responses dropped significantly to 4.9 from the rating of 8 in Scenario 1; however, one participant gave it the highest rating of 10, with the reasoning that “parking lots have less objects to interfere with satellite signals, and it is difficult to get lost in a parking lot, so it doesn't need to be that accurate”. The number of responses to each multiple-choice option to the two follow-up questions about Scenario 2 is displayed in Column 3 in Tables 4.3 and 4.4, respectively. The results show that some amount of inaccuracy in the dot’s location is acceptable to the majority of participants (eight), who consider it accurate if it can guide them to their destination. On the other hand, the most selected reason for the dot’s inaccuracy was its direction, which the participants consider to be unreliable or incorrect at times.

4.2.3 Scenario 3

Scenario 3 asked participants to provide an instance from their own experience of small-scale map navigation where they had to find something at a finer granularity level as presented in Scenario 2 (e.g., a bench in a park or a tree in a forest) using their primary map app. This question was answered by twenty-one participants, with an average rating of 7.2 for the moving dot’s location accuracy. Inductive thematic analysis [10] was performed on the qualitative data to identify relevant answers for this scenario.

The subjective responses collected for Scenario 3 mostly related to finding a building or a bus stop (18 responses), and only three responses concerned small-scale location identification: two responses pertained to finding a location inside a building with an average rating of 5 because the moving dot exhibited significant deviation from the actual location; and one response regarded locating a bench or a fountain in a park with an accuracy rating of 6 because the slight deviation of the direction was unreliable or incorrect at times. Since the responses to this question were varied in terms of granularity scale, i.e., only three responses were small-scale map navigation examples while eighteen were large-scale navigation examples similar to Scenario 1, the responses to the follow-up questions (presented in Tables 4.3 and 4.4) are also similar to the responses provided to the follow-ups of the first scenario.

4.3 PRE-STUDY

To determine the research design and methodology, including the number of accuracy levels with different error amounts, plots to choose for study tasks, and plot-distance between consecutive study tasks and other variables defined below, a pre-study was carried out, consisting of self-testing and multiple iterations of the study run with one participant. A pilot study was carried out after the pre-study to test the study design decisions and to determine further changes required before conducting the main study. The pilot study was conducted with five participants from a local university. These participants were not part of the main study participant pool (see Section 4.1.6 for participant recruitment details).

The pre-study helped determine the following variables that were controlled for the experiment.

4.3.1 Findings of the Pre-Study

- **Number of Accuracy Levels**: Different error amounts for accuracy levels were tested before finalising the final set of error rates. The results of the accuracy errors from different experimental conditions from Study 1 were referenced and tested. By evaluating the task completion success rate with different error amounts, the baseline accuracy error amount was identified to be the length of the plots' edges that were marked on the ground. The range of the accuracy levels was then formulated by using the base error amount (see Section 4.2 for different accuracy levels). With further testing, six accuracy levels were decided upon with the highest error amount of 3.4 metres which is equivalent to double the size of the base error amount selected. These six accuracy error amounts were used to establish the six experimental conditions of the study design.

- **Number of Trials**: The study took on average 60 minutes to complete. Pre-study results and observations helped determine the number of trials for each experimental condition. After assessing the amount of time it took to complete the steps detailed in Section 4.1.3 (Study Task), it was determined that two trials per experimental condition would be conducted to obtain averaged, stable measurements for each task's dependent measures.

- **Task Plots**: Plots for each trial were selected to ensure the walking distance differed from both the preceding and succeeding task locations. The minimum distance in terms of number of plots was 8, while the maximum was 14. For the client-mode application interface, the distances from the north and south ends of the plots column were 12 and 10 plots, respectively.

- **Range of Angle**: Each tap on the server-mode map changes the location of the dot that represents the participant's location in the field. With every location change, the angle at which the blue dot is displayed on the client map also changes randomly with respect to the true location of the tap that is performed on the server map. Two possible ranges were considered for determining the angle at which the client map's blue dot displays:

    - Full range: Allowing an angle to be selected at random from a complete range of 0° to 360°.

    - Restricted range: Allowing an angle to be selected at random from a range of 60° to 120°. This range displayed the blue dot on the left side of the plots column.

  Both ranges were tested in the pre-study, and it was observed that although the restricted range allowed the blue dot to be on one side of the plots column (the side where the participants were instructed to walk), constraining the dot movement would restrict the real GPS behaviour being simulated. This observation led to the full range being adopted, which resembles the GPS behaviour in real-world map applications where the moving dot that represents user location changes its position in any direction during location updates.

- **Strategies to Find a Plot**: It was hypothesized that three strategies would be employed by the participants to perform the study tasks:
    - Following the dot: Use the blue dot to see their location and find the plot highlighted on their screen by following it.
    - Counting the plots: Count the distance in terms of the number of plots to skip from their current standing location (where the last task ended) to reach the highlighted plot, and count the distance from either end of the plots column if the highlighted plot is near one of the column ends.
    - Using the landmarks: Use landmarks in the field to orient them to proceed in the correct direction and to identify the highlighted plot based on the proximity of a landmark to the highlighted plot on the on-screen map.

- **Effect of Simulated GPS**: Participants were not informed about the Wizard of Oz GPS location updates to prevent any changes in their behaviour that would affect their interaction with the study system that could arise with the knowledge that their on-screen location is determined by the experimenter and that there are chances of error in the blue dot’s location because of human error. This could have significantly affected their responses to the measures being collected during the study. Observations made of participants’ interactions with the study system and their comments during the study tasks clearly indicated that they did not suspect the location to be simulated using another smartphone handled by the experimenter. Therefore, the Study 2 findings were uncontaminated by any participant knowledge of the simulation.

- **Plot Markings**: The plots on the ground were marked using hand-made flag stakes. The west-side edges of the plots were marked by two flags (see Figure 4.3). Flags were placed at each plot's top-left and bottom-left vertices. The optimal number of flags and colours per plot marking were considered and tested in three combinations:

    - Single markings: The top-left vertex of each plot was marked using a flag stake. All the flags were the same colour.
    - Double markings and colours: Two vertices – top-left and bottom-left – of each plot were marked using two flag stakes.
        - Single colour: Both the flags used for each plot marking were of the same colour.
        - Two colours: The top-left vertices of all plots in the column were of one colour and the bottom-left vertices of the plots were of another colour.

During the pre-study testing, it was determined that the double flag markings using a single colour was the best approach for marking plots. This combination avoided two issues found in the other two flag marking arrangements:

- The single-flag markings made it difficult to figure out the start and end of a plot boundary. Selecting this flag arrangement would have required extra effort by the participants to clearly distinguish plots as separate entities on the ground.
- The double-flag markings using two flag colours were found to be a confounding variable in the experiment. The presence of two different colours made it significantly easier to browse through and single out the same-coloured flags in the plots column so as to count the number of plots to pass by to reach the target plot (highlighted in blue) by performing mental calculations.

To avoid any interference from these variables, the flag arrangement with double markings using single-coloured flags was chosen for the main study with participants.

4.4 PILOT STUDY AND FURTHER CHANGES

A pilot study was conducted after the pre-study to assess the feasibility of the research design and methodology decisions made during the pre-study phase and determine if any further changes to the study design were required before conducting the main study. Five participants were recruited from a local university to partake in the pilot testing.

The pilot study results and observations revealed participant biases regarding strategies to find target plots. To overcome these biases and prevent any interference with the study results, the following changes were introduced in the study application's client-mode application interface:

- **Map Type**: The client-mode interface of the application displayed the plots on a terrain view of Google Maps to mitigate potential bias stemming from the presence of landmarks in the field area. These landmarks were visible on the map when the satellite view of the field area was displayed. Participants made use of the landmarks displayed on the screen map to find their position on the field. This led to them focussing more on their surroundings to find their way around the study area rather than using the location dot to carry out the study tasks. As the study aimed to assess participants' use of the location information represented by the blue dot and its accuracy in determining their location, it was imperative to remove any distractors, such as landmarks, from the on-screen map view. This adjustment aimed to ensure a more accurate measurement of participant behaviour and interaction with the study system. Furthermore, change in map type aimed to replicate the agricultural field view where distinctively visible landmarks are not present.

- **Number of Plot Views**: The client-mode application interface displayed an increased number of plots in the plots column compared to the server-mode application interface. This change was introduced to prevent participants from counting the distance (in terms of the number of plots) they needed to walk from their current location to the location of the highlighted plot, a strategy observed during the pre-study that was used by the pilot study participants when a study task highlighted a plot that was closer to either end of the plots column. The plot views were extended for the client-mode interface to prevent any bias. Five plot views on both sides of the plot column were added and participants were informed that they would be looking at more plots on their screen than the actual number of plot markings on the ground. The goal was to collect participant responses for different measures to assess the usefulness of the blue dot and its accuracy; therefore, participant use of the blue dot was critical for collecting the relevant data which would otherwise be affected had they employed the *counting the plots* strategy.

- **Colours for Plot Markings**: When the study setup included marking plot edges using two colours for flags, it was observed that participants found it much easier to count plots of one colour to calculate the distance they needed to walk to complete a task. However, when single colour for flags was used, it eliminated the problem of participants counting plots rather than utilising the blue dot's location information, while still preserving the advantages of using two flags per plot marking (see Section 4.3.1 for reasons for choosing the final plot marking arrangement).

4.5 RESULTS

The results are reported for user errors (incorrect plot identifications), task completion time, subjective questionnaire responses, and NASA-TLX responses. The effect size for significant repeated measures analysis of variance (RM-ANOVA) are reported as generalised eta-squared η^2, with values <.01 considered small, approximately .06 considered medium, and >.14 considered large [17]. The post-hoc pairwise t-tests are corrected by the Holm adjustment method. No data was removed from the analysis.

4.5.1 User Errors

Each time a participant identified an incorrect plot on the ground counted as one user error. For every task in an experimental condition, participants were allowed two attempts at locating the correct plot on the ground. For the first two accuracy level conditions (with 0.0 m and 0.85 m error amounts, respectively), there were no user errors, and all participants were able to successfully identify the correct plots corresponding to the highlighted plot on the map interface of the study application. However, once the error amount increased to be the length of the plots' edge along which the participants were instructed to walk, 14 out of the total of 22 participants failed to complete the task in the third condition in their first attempt and two out of the remaining eight participants were not successful in completing the task even in their second attempt. From the fourth condition onwards (2.55 m error amount), the error in blue dot's location was more than the length of the plots' edge and therefore, as the error in accuracy increased, more errors were made by the participants in the successive tasks and the number of participants not completing a task until the second attempt increased significantly. Table 4.5 shows the success rate for completing a task in the first and second attempts by the participants.

Condition	Task	First Attempt Success Rate (%)	Second Attempt Success Rate (%)
1	1	100.00	-
	2	100.00	-
2	3	100.00	-
	4	100.00	-
3	5	63.63	75.00
	6	63.63	62.50
4	7	50.00	63.63
	8	45.45	75.00
5	9	40.90	15.38
	10	31.81	60.00
6	11	40.90	15.38
	12	45.45	33.33

Table 4.5: Task completion success rate in first and second attempts.

Table 4.6 presents the count of participants who did not correctly identify the target plot during their first and second task attempts across tasks in experimental conditions 3 to 6. Each condition comprised two tasks, denoted from task numbers 5 and 6 in condition 3 to task numbers 11 and 12 in condition 6. The error amounts associated with these conditions are 1.70 m, 2.55 m, 2.975 m, and 3.40 m, respectively.

Task	Number of participants making incorrect plot selections in their first attempt	Number of participants making incorrect plot selections in their second attempt
5	8	2
6	8	3
7	11	4
8	12	3
9	13	11
10	15	6
11	13	11
12	12	8

Table 4.6: Incorrect plot selections per task.

A one-way RM-ANOVA showed a significant effect of accuracy levels on the number of errors committed by the participants ($F_{5,21}$= 68.938, $p < .0001$, $\eta^2 = 0.767$). Figure 4.6 shows the mean errors in each experimental condition. There were no errors for conditions one and two; however, the biggest jump is seen for condition three, where the error amount was 1.7 metres, which is equal to the length of the plots' edge. Post-hoc pairwise t-tests showed that conditions two and three differ significantly ($p = .005$). There were no differences between the other experimental conditions.

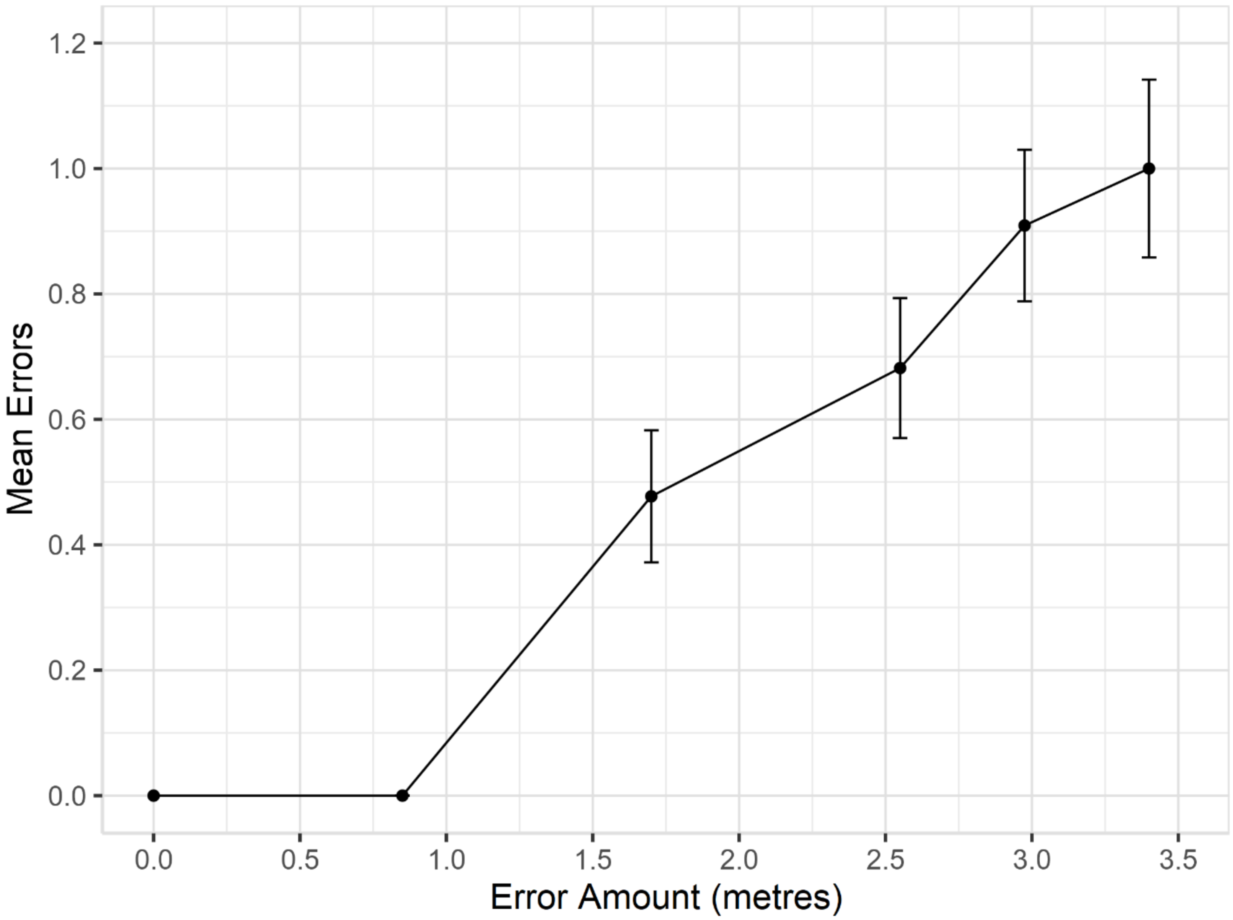


Figure 4.6: Mean errors per experimental condition.

To evaluate if participants performed better in the second task than in the first task of the same experimental condition and if the errors were reduced for the second trials, a two-way RM-ANOVA with Trial as the second factor was performed. The results showed no significant effect of the Trial on errors and there was no interaction between the two factors.

4.5.2 Task Completion Time

Task completion time was measured from the time a plot was highlighted on the screen to the time participants indicated their final plot selection on the ground. The mean task completion times for each experimental condition and each task in the experimental condition are presented in Table 4.7.

Condition	Time (Seconds)	Task	Time (Seconds)
1	40.11	1	35.23
		2	45.00
2	44.89	3	41.27
		4	48.50
3	73.68	5	80.09
		6	67.27
4	85.50	7	93.14
		8	77.86
5	92.11	9	87.77
		10	96.45
6	105.39	11	114.00
		12	96.77

Table 4.7: Mean task completion time per task and per experimental condition.

The mean task completion times increased as the conditions progressed, with the first condition taking the least amount of time (40.11 s) and the last condition taking the most amount of time overall (105.39 s). No trials were discarded for the analysis.

A one-way RM-ANOVA showed significant effect of accuracy levels of experimental conditions on task completion time ($F_{5,21} = 21.064$, $p < .0005$, $\eta^2 = 0.501$) with the effect size indicating 50% of the variance due to the factor. Figure 4.7 shows the mean task completion times in seconds for each experimental condition. There was a significant increase in the mean task completion time from condition two with accuracy error of 0.85 metres to condition three with accuracy error of 1.7 metres.

The ANOVA analysis was followed up by post-hoc pairwise t-tests that showed a significant difference between experimental conditions two and three ($p = .02$). There were no differences between the other experimental conditions.

A two-way RM-ANOVA (*Accuracy Level X Trial*) with Trial as the second factor was performed that showed an interaction between the two factors ($F_{1,21} = 7.481$, $p = .012$, $\eta^2 = 0.018$); however, there was no effect of Trial on mean task completion times.

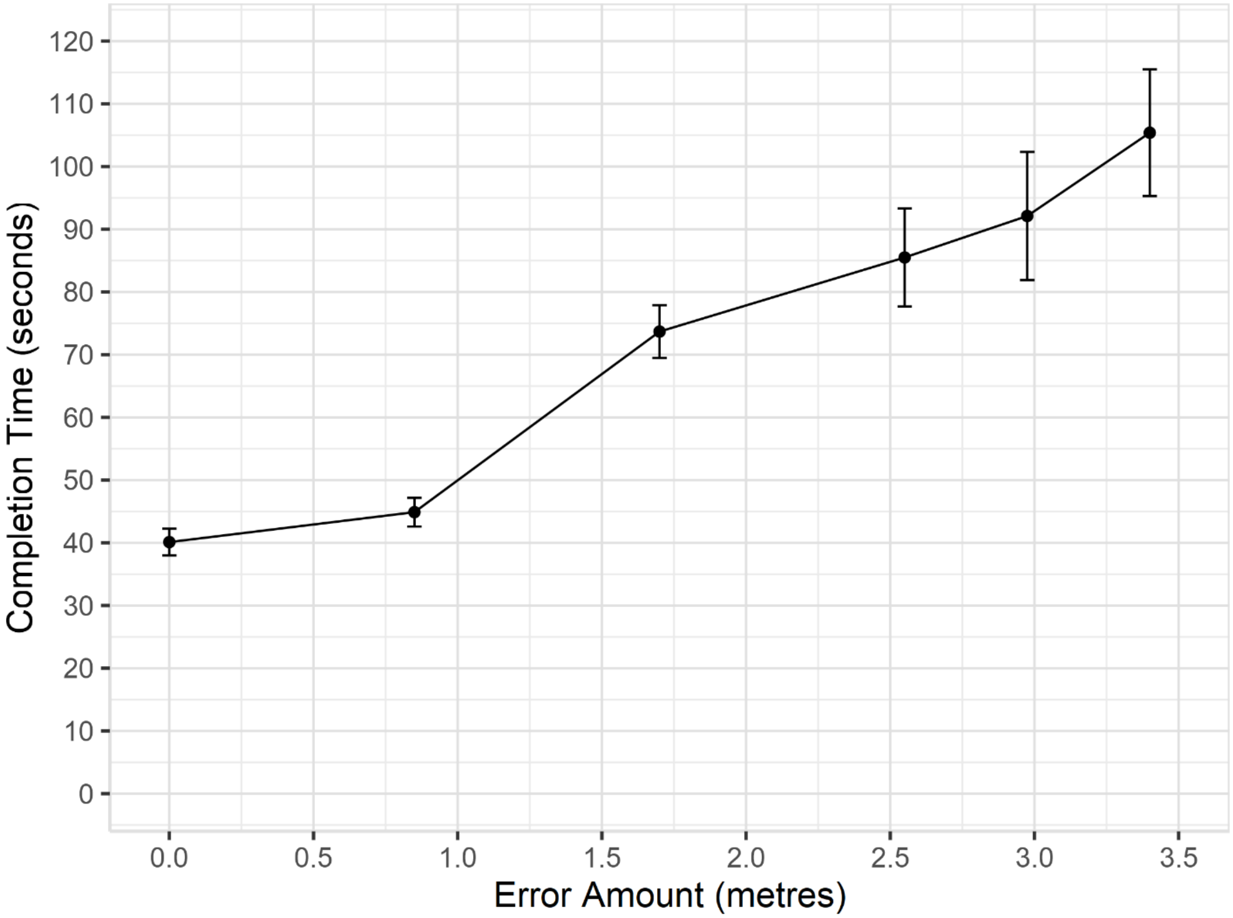


Figure 4.7: Mean task completion times per experimental condition.

4.5.3 Subjective Questionnaire Responses

Participants were asked to provide responses to the four subjective rating-scale questions after each task. The non-parametric interval data solicited from the responses on a 10-point linear scale were transformed to ranks with Aligned Rank Transform (ART) [93] before performing ANOVAs with Accuracy Level as the factor on the transformed data.

Post-hoc pairwise comparisons were performed using ART contrast tests (ART-C) [29] on the transformed data resulting from the ART analysis.

Subjective responses were collected for an open-ended question about participants’ experiences with the dot’s accuracy during the task, complementing the quantitative data gathered for the four questions. Thematic analysis [10] was conducted on the qualitative data gathered, enabling a comprehensive data evaluation through multiple iterations to identify relevant and meaningful themes. This process involved thorough familiarisation with the data, initial coding of meaningful segments, categorisation of the coded data into broader themes, and refinement of the identified themes. This process led to a systematic categorisation of participant comments and facilitated a detailed discussion in Section 5.2.5 about the various strategies employed by participants during the tasks. Additionally, it identified the main reasons influencing participants' perceptions and expectations of the dot's accuracy in Section 5.2.6.

4.5.3.1 Question 1: How much did you use the dot?

The one-way RM-ANOVA results showed significant effect of accuracy levels of experimental conditions on participants’ use of the dot throughout the study ($F_{5,237}= 6.363$, $p < .0001$). Follow-up pairwise comparisons showed no significant differences between the experimental conditions.

The mean rating for Question 1 in each experimental condition is shown in Figure 4.8. A decline in rating occurred when the first error amount was introduced in 0.85-metre error condition, continuing with gradual downwards slope until the last experimental condition with 3.40 metres of error in location accuracy.

A two-way RM-ANOVA (*Accuracy Level X Trial*) showed no significant effect of Trial on ratings for Question 1, and there was no interaction between the factors.

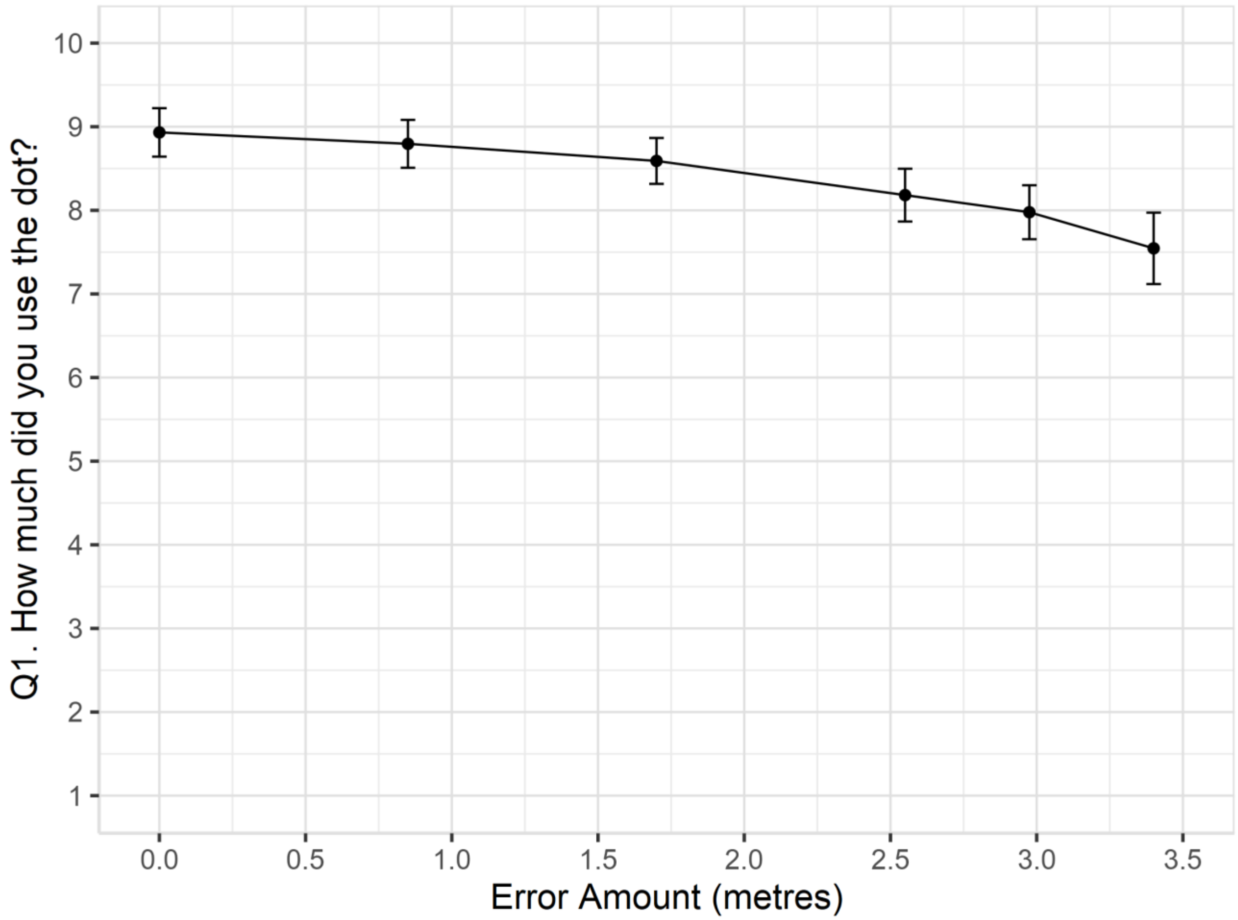


Figure 4.8: Mean rating of participants' use of the dot per experimental condition.

4.5.3.2 Question 2: How much did you trust the dot?

The one-way RM-ANOVA results showed a significant effect of accuracy level on participant trust in the location information provided by the dot ($F_{5,237}$= 47.876, $p < .0001$).

The follow-up comparisons showed significant differences between the 0.0-metre error condition and 0.85-metre error condition ($p = .01$), and between the 0.85-metre error condition and the 1.70-

metre error condition ($p < .0001$). There were no significant differences between any other experimental conditions.

Figure 4.9 shows a declining trend in participants' mean rating for Question 2 over the conditions.

A two-way RM-ANOVA (*Accuracy Level X Trial*) showed no significant effect of Trial on the ratings for Question 2, and there was no interaction between the factors.

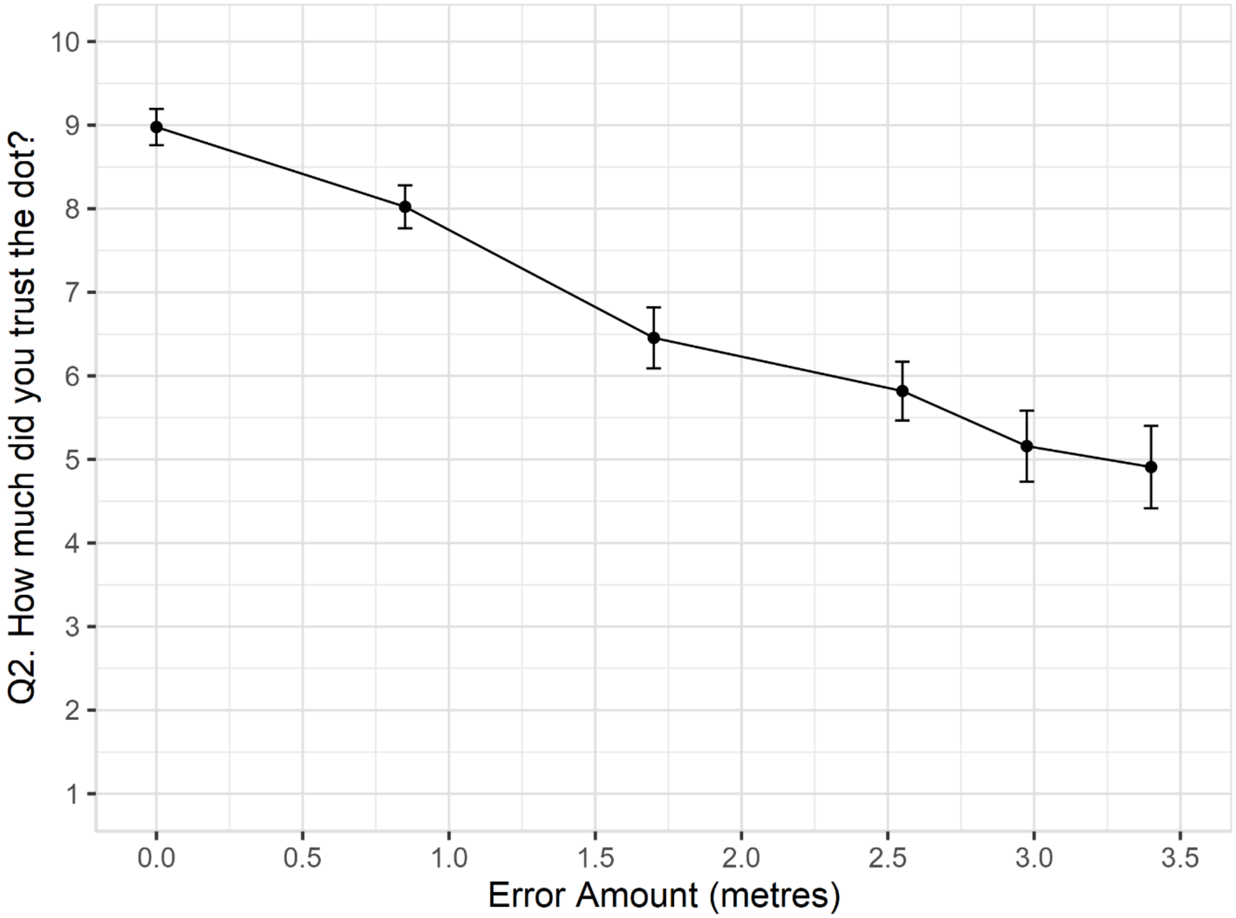


Figure 4.9: Mean rating of participants' trust in the dot per experimental condition.

4.5.3.3 Question 3: How accurate was the dot?

The one-way RM-ANOVA results a showed significant effect of accuracy level on the participants' perceived accuracy of the dot location ($F_{5,237}$= 92.306, $p < .0001$).

Post-hoc pairwise comparisons showed significant differences between the 0.0-metre error condition and the 0.85-metre error condition ($p = .001$), and between the 0.85-metre error condition and the 1.70-metre error condition ($p < .0001$). There were no significant differences between other experimental conditions. However, the difference between the 2.55-metre error condition and the 3.40-metre error condition was significant ($p = .001$), since the 2.975-metre error condition was an intermediate condition. Figure 4.10 demonstrates a significant decline in mean accuracy ratings over time, indicating that as the error in dot location increased with each experimental condition, participants perceived the dot as being less accurate.

A two-way RM-ANOVA (*Accuracy Level X Trial*) showed significant effect of Trial on ratings for Question 3 ($F_{5,237}$= 4.769, $p = .029$), however, there was no interaction between the factors. The follow up tests showed no differences between the successive pairs of experimental conditions.

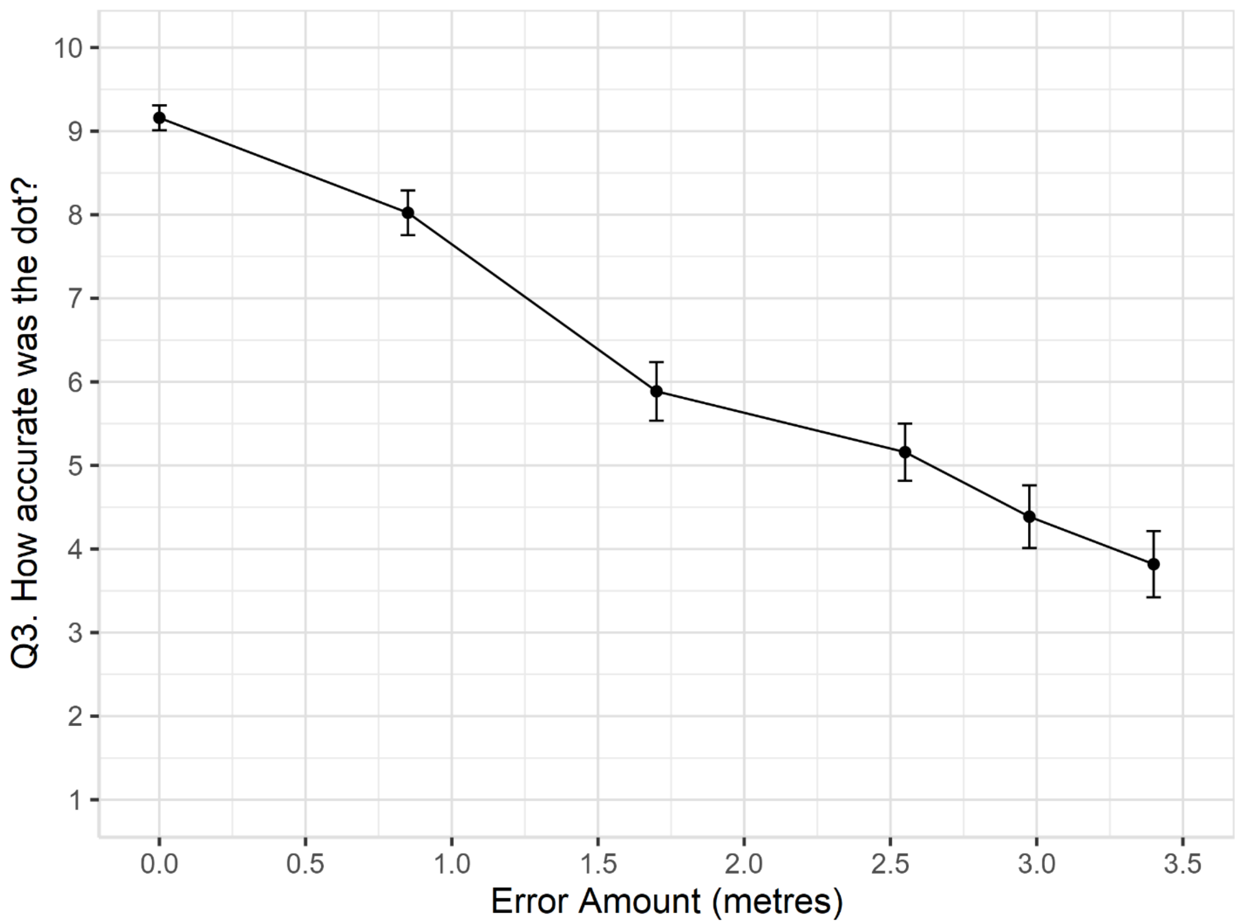


Figure 4.10: Mean rating of participants' perceived accuracy of the dot per experimental condition.

4.5.3.4 Question 4: How useful was the dot?

The ANOVA results show a significant effect of accuracy level on participants' perceived usefulness of the dot ($F_{5,237}$= 65.283, $p < .0001$).

Follow-up tests showed significant differences between the 0.85-metre error condition and the 1.70-metre error condition ($p < .0001$), and between the 1.70-metre error condition and the 2.55-

metre error condition (p = .003). There were no significant differences between any other experimental conditions. There was a significant difference, however, in the perceived usefulness of the dot (p = .04) when the 2.55-metre error condition and the 3.40-metre error condition were compared. Figure 4.11's representation of the mean ratings for Question 4 reveals a general downward trend.

A two-way RM-ANOVA (*Accuracy Level X Trial*) showed no significant effect of Trial on the ratings for Question 4, and there was no interaction between the factors.

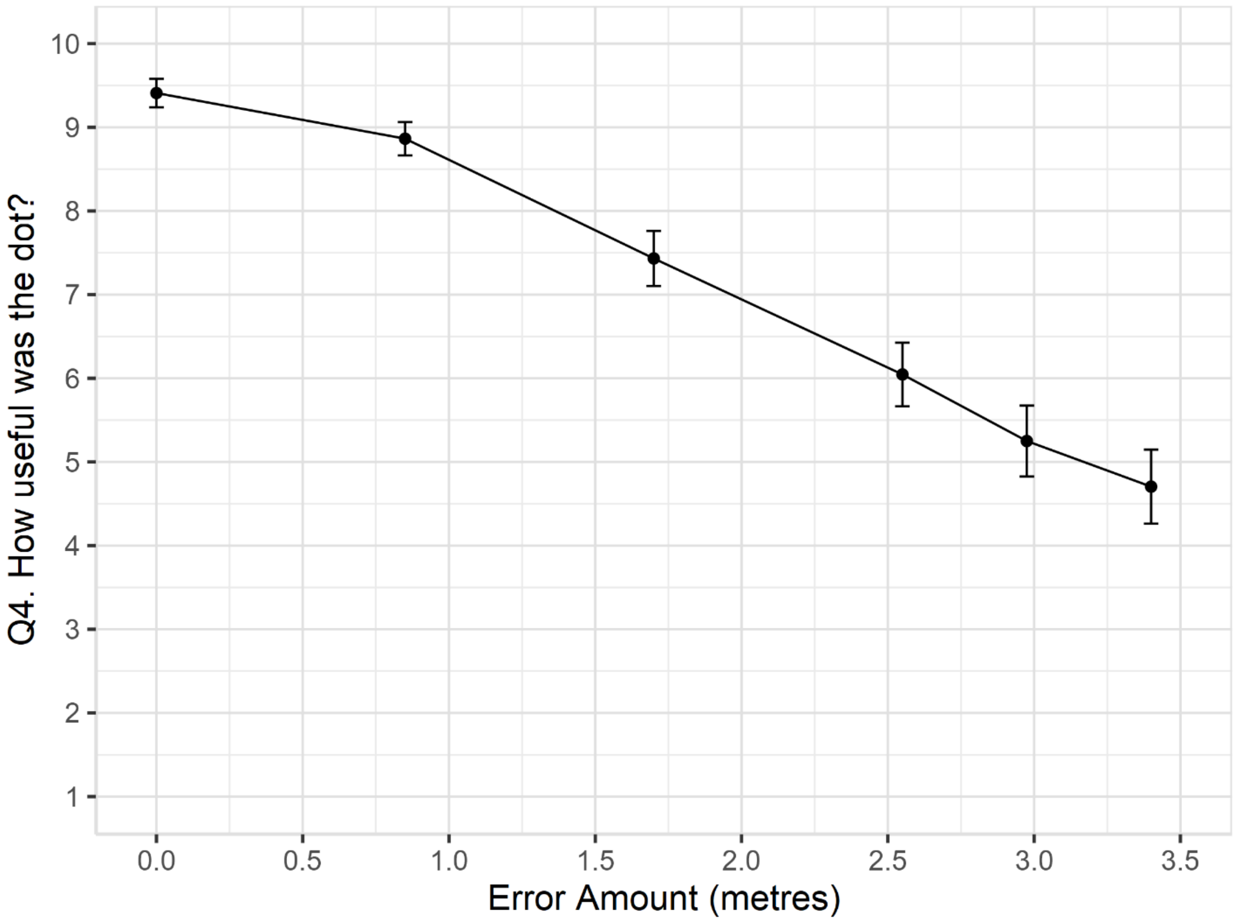


Figure 4.11: Mean rating of participants’ perceived usefulness of the dot per experimental condition.

4.5.4 Task Load Index Responses

The Aligned Rank Transform was performed on the NASA-TLX responses, and the transformed ranks results were passed to RM-ANOVA to study the effects of accuracy level on each of the TLX questions. The results of the analysis revealed significant effects on the responses to all the questions (see Figure 4.12). Post-hoc pairwise t-tests were performed using the Aligned Rank Transform Contrast tests.

There were significant effects of accuracy level on each of the following: mental demand ($F_{5,105}$= 25.281, $p < .0001$), physical demand ($F_{5,105}$= 10.343, $p < .0001$), temporal demand ($F_{5,105}$= 5.2914, $p < .0001$), perceived performance ($F_{5,105}$= 16.885, $p < .0001$), frustration ($F_{5,105}$= 20.227, $p < .0001$), and perceived overall effort ($F_{5,105}$= 19.407, $p < .0001$). The follow-up ART-C analysis showed significant differences between the experimental conditions for only mental demand, perceived performance, and perceived overall effort. For mental demand, there were significant differences between 0.85-metre error condition and 1.70-metre error condition only ($p = .0282, < .05$). Significant differences between these two conditions were also observed for the participants' perceived performance, with $p = .05$, and between 1.70-metre error condition and 2.55-metre error condition only ($p = .0476, < .05$) for their perceived overall effort during the study.

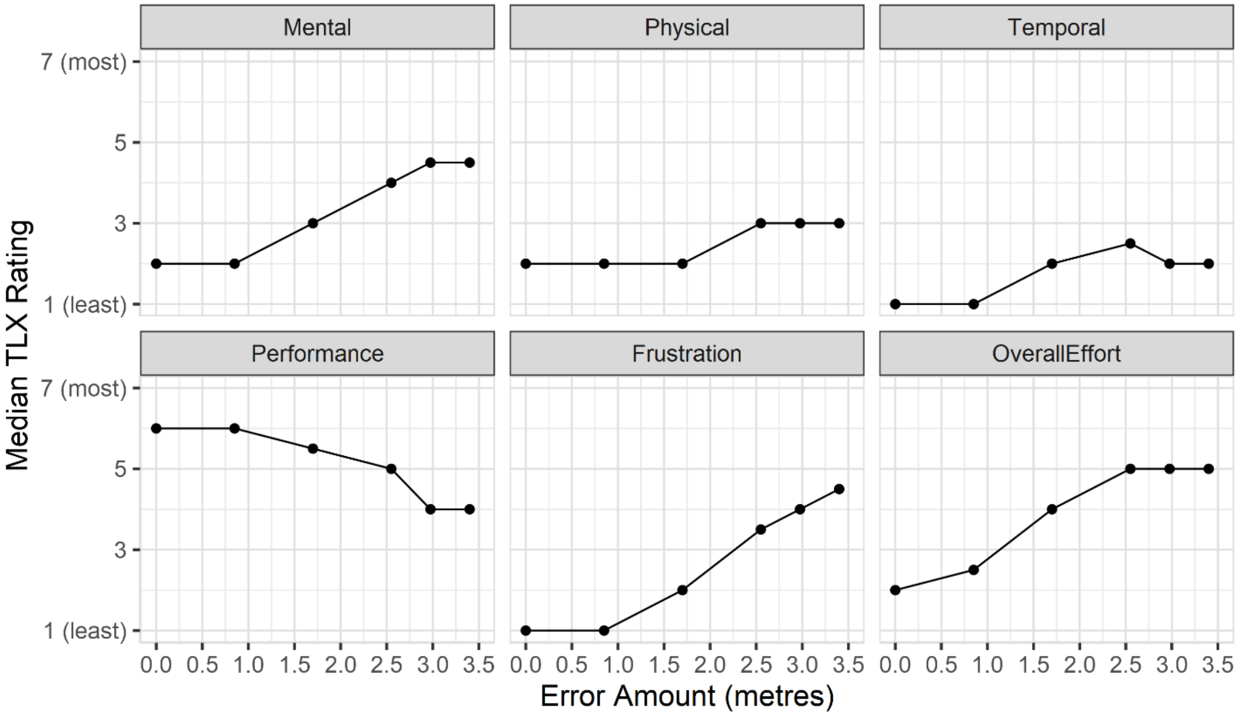


Figure 4.12: Median NASA-TLX ratings of participants' mental, physical, and temporal efforts, and their perceived performance, frustration, and overall effort per experimental condition.

4.5.5 Strategies Used for Task Completion

After the completion of the study, participants answered a post-study questionnaire that asked them to estimate their use of the strategies for completing the tasks in terms of percentage and to respond to one open-ended question regarding their own strategies that helped them complete the tasks. Participants were expected to have used two strategies: *following the dot* and *counting the plots*; however, they were also asked to specify any other strategies they used while completing the tasks in addition to these strategies. Inductive thematic analysis [10] was carried out on the subjective responses received regarding the strategies used by the participants for task completion. Participants' responses were first broadly categorised into similar themes using colour coding and labelling using relevant keywords. These initial themes were then revisited for a thorough evaluation of identical ideas using multiple iterations of data assessment, which led to the identification of distinct strategies discussed in detail in Section 4.5.5.3.

4.5.5.1 Strategy 1: Following the Dot

This strategy was employed by all the participants. The following statistics elaborate on their use of this strategy during the entire duration of the study.

- Sixteen participants' usage of this strategy was greater than 50% during the study. The average of their usage is 75%.

- Two participants stated exactly 50% use of this strategy during the study.

- Four participants' strategy use was less than 50% during the study. The average of their usage is 32.5%.

Strategy Usage	Number of Participants	Average Usage
Greater than 50%	16	75.00%
Equal to 50%	2	50.00%
Less than 50%	4	32.50%

Table 4.8: Strategy 1 participant usage during the study.

4.5.5.2 Strategy 2: Counting the Plots

Only thirteen participants out of the total of twenty-two reported using the strategy of *counting the plots* for performing the tasks.

- Only two participants used this strategy more than 50% of the time for completing their tasks, with an average of 72.5% usage during the study.

- Eleven participants reported using this strategy less than 50%, with an average usage of 19.5% over the course of the study.

Strategy Usage	Number of Participants	Average Usage
More than 50%	2	72.50%
Less than 50%	11	19.50%

Table 4.9: Strategy 2 participant usage during the study.

4.5.5.3 Other Strategies

Eight of the twenty-two participants mentioned using either of the two strategies (*following the dot* or *counting the plots*) for completing their tasks and did not report using any other strategies. Fourteen participants mentioned using other strategies to supplement the two strategies, which enabled them to reach the general area of the highlighted plot when the error in the dot's accuracy was high. Once they were in the vicinity of the highlighted plot, these participants reported using the following strategies to identify the plot highlighted on their map screen on the ground:

- Observing Dot Sensitivity and Movement Patterns

  Four participants' strategy was to observe the patterns of dot movement, especially towards the end of the trial when they were in the vicinity of the highlighted plot. They observed the overlapping of locations where the dot was moving with their movements and selected the plot over which most of the overlapping occurred.

- Dot Distance to the Highlighted Plot

  Five participants used a strategy based on the smallest distance from the dot to the highlighted plot on the screen. They walked along a few plots and where they found the least distance from the dot to the highlighted plot, they chose that plot as their answer.

- Experience with Previous Tasks

  Two participants used a strategy that involved paying attention to the position of the dot with respect to the highlighted plot in the previous task and tried to apply the same strategy of choosing a plot where the dot position aligned with a plot in the same manner. They were aided in this strategy by getting familiar with the accuracy error in the first task of the same condition, which helped them in the second task.

- Intuition and Guess Work

  Three participants reported that they had guessed the plot location when they were confused between two or three plots where the dot was indicating their location.

CHAPTER 5

DISCUSSION

This chapter discusses the findings and observations from the two research studies presented in Chapters 3 and 4 of this thesis. The summaries of the main results from the two studies are followed by detailed discussions in the subsections that follow.

Both the studies found several significant results:

- Study 1 obtained the following outcomes:
    - Different device and network settings affect the accuracy and precision of location data collected on a smartphone.
    - The *Location+AirplaneMode* condition exhibited higher accuracy and precision compared to the other three experimental conditions, with an average Accuracy Error of 3.88 metres, Precision Error I of 0.97 metres, and Precision Error II of 1.62 metres.
    - Clear skies or less obstructions, such as fewer clouds, were found to result in more accurate and precise location readings. For example, location measurements on the day with the most cloud cover (day 6) for the *Location+MobileData* condition had a mean accuracy error of 6.09 metres, compared to a mean accuracy error of 3.78 metres on day 4 which had no cloud cover.

- Study 2 provided the following results:
    - Participants made no errors in the experimental condition that had an error amount less than the length of the edge of the plots that were marked on the ground.

    - The success rate for task completion decreased starting from the experimental condition with a 1.70 metres error when the error amount equaled the length of the plots’ edge, and increased for the conditions with 2.55 metres, 2.975 metres, and 3.40 metres of error.
    - As accuracy decreased, task completion time and user error count increased.
    - Seventy-three percent of the participants reported using the strategy of *following the dot* for over fifty percent of the time during the study, even when they were aware of errors in the on-screen representation of their location on the map.

5.1 DISCUSSION OF STUDY 1 RESULTS

5.1.1 GPS Accuracy and Precision

The location coordinates (latitude and longitude) for the testing location contained errors in accuracy and precision, which meant that the location indicated on the on-screen map did not correspond to the real-world location for which location data collection was conducted. The low accuracy and precision indicated that the location coordinates from a smartphone GPS system could not be used to find or re-locate an exact location point on the ground in a real-world environment. It was concluded from the results of the study that the location information shown on the map can only help point a user to the area where the target location is, and users would need to make location adjustments on their own in order to find the target location.

The accuracy and precision of the location data collected for Study 1 were affected by the different device settings. Data analysis showed that when airplane mode was active and only the device location setting was enabled, the location data had higher accuracy and precision compared to the other three device settings. The reason behind comparatively accurate and precise location readings is that even when other network settings such as Wi-Fi and mobile data are disabled on the device, the airplane mode blocks the device’s wireless communication functions, which may reduce interference with the reception of signals by the GPS receivers and sensors on the smartphone.

The location data's accuracy and precision were also affected by the weather of the day. More accurate and precise readings were recorded on days with clear sky or less disruptive sky conditions than on days with cloud cover, which causes GPS signal interruptions [40, 88].

High error rates in the location data from the smartphone GPS motivated the use of simulated GPS data in Study 2, where the field tasks (plot identification at different levels of location accuracy) were designed to be performed in a field setup and layout similar to plots in an agricultural field. The amount of error in the different experimental conditions was controlled to understand the effects of location inaccuracy on user behaviour, performance, and trust in the study system over the duration of the experiment.

5.1.2 External Factors

The accuracy and precision of location data were affected by the sky cover conditions of the day. Comparatively more accurate and precise location data readings were recorded on days with less disruptions such as fewer clouds and light snow than on days with extensive cloud cover (see Tables 3.4 and 3.5). The lowest accuracy values were computed from the data across all the experimental conditions on days with broken clouds, which caused GPS signal interruptions. However, precision was compromised by both light snow and broken clouds.

There is no significant difference between the weather conditions on days when the most accurate readings were recorded versus when the least accurate readings were recorded. This is evident from the fact that broken clouds condition was present during both days under the *Location+WiFi* condition, when both the most accurate and the least accurate readings were recorded for accuracy. Similarly, light snow conditions were recorded for both days when the highest and the lowest precision values were computed from the location data under the *Location+MobileData* condition.

While a definitive conclusion cannot be drawn about the weather from this data regarding the sky cover conditions, it is apparent that more accurate location readings were achieved when the sky was clear or had fewer disruptive elements, such as a few clouds, compared to days with cloud cover or light snowfall.

5.2 DISCUSSION OF STUDY 2 RESULTS

5.2.1 Location-Finding Tasks

The results of Study 2 showed an increase in unsuccessful task completion attempts and the corresponding completion times as the error amount increased in each experimental condition once the error amount was equal to the length of the plots' edge. The 1.70-metre error condition was the first experimental condition where participants began to make mistakes in identifying the correct plots. These mistakes were a result of the error in their on-screen location that offset the dot's coordinates by the error amount that caused participants' location representation to be displayed at a different place on their map compared to their actual position where they were walking or standing in the field. Because the error amount was equal to the length of the plots' marked edge, participants' on-screen location was likely to be offset by one plot, which led them to select an incorrect plot one plot away from the correct plot location. This happened when the angle of displacement was strongly inclined towards either the north or south directions.

The angle of displacement is the direction in which the participant's displayed location on the screen differed from their actual physical location in the field. A significant angle of displacement increases task difficulty by hindering participants' ability to accurately correlate their on-screen location representation with the correct physical location.

Starting from the 1.70-metre error condition, the amount of error causing the participant's location to be displayed significantly off in the north or south direction made it more challenging for them to identify the correct plot. Participants traversed along the marked plot edges in only two directions: north and south, without considering the east or west directions for the tasks. As a result, participants had to determine their movements in the north or south direction based on the dot's representation of their location on the ground. When a change in the angle of displacement resulted in the blue dot being displayed on the east or west side of the true location and the participants selected the plot based on the dot's location on the map, it resulted in no mistakes. This occurred because the dot represented their proximity to the highlighted plot with sufficient accuracy, whether it appeared in front of the plot or within its perimeter.

Figure 5.1 presents the map view of the client-mode application interface, illustrating the impact of the angle of displacement on participants' selection of the target plot on the ground. The left part of the figure demonstrates dot displacement in the north direction. The blue dot represents a participant’s location, which is one plot away from the centre of the target plot highlighted in blue. In this scenario, the participant was in front of the correct plot; however, the observed position of the blue dot was shifted to the adjacent plot. The participant, perceiving their location as being one plot off from the correct position, adjusted their real-world position by moving one plot south. This adjustment led to the selection of an incorrect plot, shown as the shaded plot. On the other hand, the right part of the figure displays dot displacement in the west direction. Despite this displacement, the participant's location representation on the map was still positioned in front of the target plot. As a result, the participant accurately selected the correct plot.

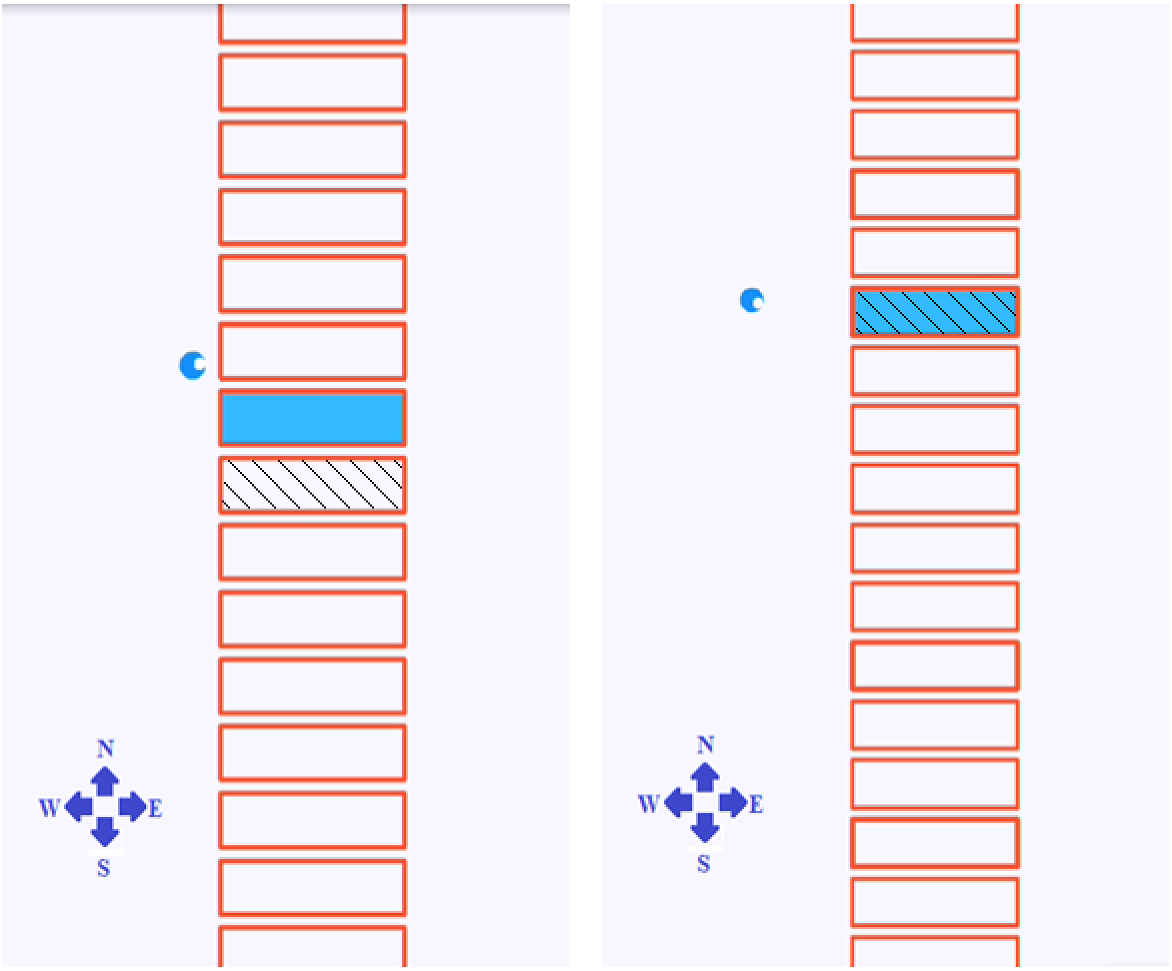


Figure 5.1: The effect of the angle of displacement on the blue dot's location: the dot location is off by one plot as viewed on the client screen when the participant is in front of the correct plot highlighted in blue (left); the blue dot is displaying in front of the target plot when the participant is in front of its edge (right). The shaded plots represent the participant's final selections in both cases.

When the angle fell within the ordinal directions (i.e., Northeast, Southeast, Southwest and Northwest) or other subdivisions between the cardinal (i.e., North, South, East and West) and ordinal directions, it was observed that the participants attempted to interpret the directional information by associating it with the two directions that they were concerned with – north and south. In other words, if the angle leaned more towards the north, they would decide to walk in that direction, and vice versa for angles leaning away from the north.

Similar results were observed with the 2.55-metre, 2.975-metre, and 3.40-metre error conditions when the error amount exceeded the length of the plots' edge. Since the error rate increased with each successive experimental condition, the dot displacement was also higher, leading to participants selecting plots that were two or three plot-length away from the highlighted plot in either direction (north or south).

5.2.2 Tasks Per Experimental Condition

Since there were two tasks in each of the six experimental conditions, participants found it useful to perform the second task of a condition with a certain error amount in the blue dot's location after having completed the first task. One of the participants mentioned that "it was a good idea to have me do two different tasks at the same condition because when I did the second task, I got more used to and comfortable with the accuracy [of the dot] as I did the second task". Although the experience of working on the first task of an experimental condition was useful to them, it was not reflected in the overall average task completion times of all experimental conditions, where only half of the second tasks were completed in less time than the first tasks (Table 4.7). In the experimental conditions where second tasks were completed more quickly, the average completion time for the second tasks was 80.64 seconds, compared to 95.74 seconds for the first tasks. This outcome depends on two factors: first, some participants solely followed the dot and therefore only selected a plot when the dot indicated a location of the highlighted plot; second, after understanding how the dot moved with the current error rate, participants took extra time to configure their location and adjust to it.

5.2.3 Task Attempts

For each task of the six experimental conditions, participants were allowed two attempts at identifying the highlighted plot on the ground. The first attempts helped participants understand the dot's behaviour and approximate the error amount added to its location that led to successful second attempts by many participants in experimental conditions with error amounts of 1.70 m, 2.55 m, 2.975 m and 3.40 m. This observation was noted for each participant during the study (Table 4.5). It was concluded that the participants' observations of the dot movements helped them understand and estimate the error to correct their location based on their on-screen location. However, the success rate dropped for three out of the four tasks in the 2.975-metre and 3.40-metre error conditions. This could be the result of the increase in mental demand that the participants felt when completing tasks at much higher error rates in these two experimental conditions. This also tested the participants' patience while working with the dot locations, as they reported higher frustration and overall effort ratings for the 2.55-metre, 2.975-metre and 3.40-metre error conditions (Figure 4.12).

With the onset of user mistakes at the 1.70-metre error condition, the number of participants making incorrect plot selections in their first and second attempts increased over time (Table 4.6).

The 1.70-metre error condition was the first experimental condition where the error amount caused the dot displacement to increase to the length of the plots' edge. Therefore, if the distance is one edge length long, and the angle at which the dot shows on the participants' screen diverges randomly in any direction, it becomes difficult to judge where the correct plot is on the ground. In this case, the participants found it challenging to select one plot from among the two or three plots that they were uncertain about.

A significant increase in the number of errors in the second attempts happened in the 2.975-metre and 3.40-metre error conditions. This was due to the error amount in the dot's location being close to double the length of the plots' edge in the 2.975-metre error condition and double in the 3.40-metre error condition.

5.2.4 Subjective Ratings of Dot Behaviour

The average ratings from the four subjective questions (Section 4.10.3) revealed a consistent trend: the highest ratings were observed in the first experimental condition, where no user errors occurred, whereas the lowest ratings were recorded in the last condition with a 3.40-metre error amount. Despite this trend, individual variations in ratings were notable among participants.

Regarding the first question, focusing on participants' ratings of dot usage during tasks, seven participants consistently rated their usage as 10 for all twelve tasks. Conversely, one participant rated their usage as 9 for all tasks except one, where they rated it as 10. These participants heavily relied on the dot as their sole reference point for estimating their location on the ground, matching their on-screen location depicted by the blue dot. Additionally, two participants increased their ratings from the 2.55-metre error condition through the 3.40-metre error condition due to continuous dot referencing during their movements near the area of the target plot. Another participant increased their ratings starting from the 1.70-metre error condition, complementing their *counting the plots* strategy with dot referencing for location confirmation. Similarly, participants who initially rated dot usage lower in lower-error conditions because they were able to easily find the correct plots without referring to the dot for the entire duration of the tasks increased their ratings as higher-error conditions demanded increased reliance on the dot for accurate location estimations.

The second question assessed participants' trust in the dot's location accuracy. Fourteen participants demonstrated a consistent decrease in ratings from the first to the last experimental condition, mirroring the increased error in accuracy. However, four participants consistently rated high (8-10), trusting the dot more than others due to comparisons with other map applications. One of the participants commented, "If I compare to Google Maps or Apple Maps, I think it's quite good because I am still next to the area. If we compare to the larger building, this is a very small area, so if we compare to the larger building, then I'm still landing on the right place, so it's still very accurate." Additionally, one participant provided high ratings (9-10) for all the tasks except the first task with a decrease in trust (6) in the 1.70-metre error condition, likely because this was the first condition where accuracy error affected user performance and led to user errors. However, the continued high ratings for the subsequent tasks could likely be because this participant only used the strategy of *following the dot* and found it useful to find the general area of the target plot in higher-error conditions.

In the third question, evaluating participants' ratings of dot accuracy, most participants' declining ratings reflected the expected results as the accuracy reduced over time. Nevertheless, three participants maintained high ratings based on successful plot identification, attributing their role in understanding the dot's behaviour crucial to their accuracy assessments. Furthermore, seven participants changed their ratings from the high-to-low trend in some tasks, reporting instances where the dot's location led them to select the correct plot on the ground. This happened when the dot landed in front of or inside a plot's boundary, and they trusted its location when selecting a plot on the ground that proved to be the correct plot.

The fourth question on the dot's usefulness in finding the correct plot revealed a similar trend. While most participants displayed a high-to-low rating pattern, three consistently rated the dot above 8, emphasizing its assistance in reaching the correct area of the target plot. These participants were only unsuccessful in 1-2 tasks during the study. Conversely, seven participants decreased their ratings due to discrepancies between their physical location and the dot's position, impacting their plot selection on the ground. One of the participants stated that "the dot was around the correct area but not where I was walking or standing", another said that "the dot did not land me in the right box", and another commented, "No matter where I stand, it is still one or two plots away from me". Another seven participants increased their ratings in the higher-error conditions, acknowledging the dot's assistance in either guiding their plot selection or aiding in the estimation of the target plot's location.

5.2.5 Strategies For Task Completion

The two strategies anticipated to be used by the participants – *following the dot* and *counting the plots* – were significantly used by all the participants, as the results of the second study revealed. All participants successfully completed the four tasks for the 0.0-metre and 0.85-metre error conditions, which made them trust the dot information. The 1.70-metre error condition was the first experimental condition where the participants started making errors. Their trust ratings, except for five participants, were significantly reduced by the increased error rate. As a result, even when they did not trust the dot enough to rely on it to identify the correct plot, they did use it to guide them and take them closer to it. One participant reported, “This time I noticed that the blue dot does not move accurately, and it seems to me it jumped. That's why I did not trust it and moved slowly”. However, there were other participants who, despite the increased error rate in dot location, continued to find it useful. This trust was reflected in their performances where, whether successful or not, they gave near-perfect or full ratings for their trust in the dot’s representation of their location. One of them stated that “the dot was useful in helping me find the pattern of GPS, like it was moving away and near depending on my proximity to location, so I adjusted myself to the situation for finding the desired plot”.

For the 2.55-metre error condition, the error amount in dot location increased further; it was observed that instead of relying on the dot to reach the highlighted target plot, the participants started *counting the plots* on the on-screen map to figure out how many plots they needed to pass by on the ground. One of the participants commented, “I counted the plots on the device to try and find the correct one in addition to using the dot”. Some participants reported not trusting the dot with increased error in its location and therefore adopted the strategy of *counting the plots* to complete the tasks. One participant recounted, “Sometimes I would use the dot as a starting point, count, and check where the dot is, and disregard the dot if I felt it was inaccurate”. There were some participants who, in this experimental condition where the error amount was greater than the length of the plot edge, started paying close attention to the behaviour of the dot movements to figure out the error amount so as to adjust for it. This helped some of them to approximate the correct plot on the ground by estimating the error amount based on how the dot moved. One participant mentioned, “Actually, it doesn’t show the correct place. I have to decide between the two boxes. I used averaging because it was fluctuating between the two places, so I used my approximation”. Another participant explained, “I found correct plot with counting the movements [of the dot] between adjacent plots to get average [of the dot location]. I waited for two recalibrations before moving [to the next location] to give increased data for averaging”.

In the 2.975-metre error condition, again, since the error was much higher than in the 2.55-metre error condition, participants spent more time pacing up and down beside a few plots while considering which would be their choices for the correct plot. By doing so, some of the participants were trying to estimate the maximum overlap of dot appearances that would lead them to the plot corresponding to the highlighted plot on the screen. Some of them were consistent in *following the dot* and therefore selected a plot only when the dot appeared in front of or on the edge of the highlighted plot on their screen. Since many of the participants did not trust the dot anymore, they counted the plots from their previous location to the current task’s highlighted plot on the screen and walked past a number of plots to reach the target plot.

Some participants were not able to estimate the location of the target plot based on dot behaviour and error, nor did they count plots to skip over; instead, they reported using their intuition or applying guesswork. Asked how they found the plot, one participant replied, “I guessed”. Another participant responded, “I mostly just tried to watch how the dot was moving and use my failures [in previous tasks] to help me with my next guess. I attempted to count the plots during condition 3 and 4 but found no success”.

Some participants also mentioned that they were selecting plots based on the location of the dot the last time they either identified the correct plot or were informed of the correct plot location, i.e., information about how close and in which direction the dot was to the correct plot on their map screen. One participant said, “I remember that, like in the last task, the dot was in front of the correct plot, and in this one, the dot is again in front of the plot, so I had to choose between this one and this one. So the dot [is] in front of this one, so I guess this”. This participant paid attention to the patterns observed in the previous tasks, assuming that the dot would behave in a similar manner in the current task as well, instead of factoring in the error amount present in the dot's location and estimating their correct location by adjusting their location on the screen. One participant's comment was, "Basically, I follow the dot, and whenever I am in the same location as the previous [task] time, I remember the position of the dot and start relating it to the previous time, like what angle the dot settled at the previous time and how it will be for the second time as well".

Some participants who successfully completed the first task in this experimental condition were not able to find the correct plot in the second task, despite the same amount of error encountered during the first task. This could have resulted from misjudgment, incorrect estimations of the dot's location, or from only *following the dot* and not employing any other strategy, i.e., only selecting a plot based on which plot the dot landed on the map without taking the error amount into account. In this case, even when they were standing at the corner of a plot the dot had pointed to, they would not be standing by the edge of the target plot on the ground. Their position on the ground would be at least one and a half plots away from the target plot. In this accuracy level condition, the participants who chose a plot based solely on the dot's location may have done so because they trusted the dot completely without considering the error amount of the experimental condition, or because they were exhausted from spending a long time completing the task. As a result, they either gave up on trying to locate the correct plot and instead used their own calculations, or they were under the impression that, although there was an error in the dot's location, the dot must occasionally land on the correct plot as had happened in the previous accuracy level conditions with lower error rates.

In the 3.40-metre error condition, only nine participants out of the twenty-two successfully completed task 1, and only ten participants completed task 2 without any unsuccessful attempts. The participants who made mistakes were either choosing a plot by only *following the dot* or were unable to correctly estimate the error and adjust their location accordingly. Thirteen participants were observed *counting the plots* before starting the tasks in this condition, a behaviour that was confirmed by their responses to the post-study questionnaire. They counted the plots because the error was significantly higher than in the previous conditions (the error amount was double the length of the plots' edges) and their experience with the previous conditions' tasks taught them that the dot did not display their correct location. This led the participants to count the plots, with the expectation that they would land on the correct plot on the ground. This was true in most cases, except when the participants miscounted and were off by one to three plots. Miscounting was usually due to a distraction. For example, one participant said, “I think I tried counting in the third condition, but I got distracted. I was like, maybe I could count, take the dot, and then match the dot to the counting, but I got distracted”. Another commented, “I normally counted and then I go to the plot, but this time I look at the dot [and think] ‘what's it doing?’ and it's doing weird stuff, so I lost my counting and was like ‘okay was it 10 or 11?’”. Another reason for miscounting was reported by a participant who stated, “I made a mistake between counting how many spaces [there are] between the plots or how many [plots there are] to the [target] plot, so that'll be a difference between 12 or 13 plots”. In this case, the participant counted the gaps between the plots instead of *counting the plots* themselves in order to reach the target plot.

The participants who selected their answers based on only *following the dot* stated that they trusted the dot because it was their only point of reference while navigating the field area. One participant commented, “I could not use any kind of guess or some other thing to find the plot. I only trusted the dot”. While there were some participants who did not think of *counting the plots* as a possible solution, as evident from the previous participant comment, some explained that they would not be counting any objects in real life and would therefore only be relying on *following the dot* for performing their tasks. One of the participants commented, “I would depend on the system rather than using my own counting method. I have used the counting at the end [of the study], but I couldn’t keep in mind the block where I started so didn’t use it. It didn’t make sense. I won’t be able to figure where I was previously [to recount plots in case I made a counting mistake]”.

The participants who were only *following the dot* did not take account of the error in dot locations when they estimated the location of the highlighted plot on the ground. This was evident from one participant’s comment explaining how they selected a plot, saying, “The last one was wrong, but it (the dot) was showing that I was on top of the blue box. But this time, it wouldn’t ever let me go close to the blue [plot], so I just tried the next one”. These participants’ sole reliance on *following the dot* to select the target plot was based on their strict adherence to the task instructions given to them prior to starting the study. These instructions directed them to make use of the location information shown by the blue dot on their on-screen map to try to locate the highlighted plot on the ground. Another reason the participants provided for *following the dot* was the difference between the number of plot views displayed on the client-mode application interface and the number of plots marked on the ground. The participants were unable to correlate and match the on-screen plots with the plot markings on the ground as a result of the different plot views, which made them more likely to trust the dot. One participant commented, "Because there is not any exact similarity between the number of plots on device and on the ground, I focus only on the blue dot”.

Following the dot was a straightforward strategy that required the least amount of mental effort. The participants who relied solely on this strategy must have used it to complete the tasks with higher error rates in the same amount of time they were able to complete the tasks with lower error rates. Their NASA-TLX responses showed high ratings for all measures, and their post-task feedback highlighted their reasons for not employing other strategies for completing the tasks. This participant behaviour was evident from some of the comments that indicated that they did not try hard to find the correct plot on the ground, but instead wanted to just complete the task, which they considered to be completed once they selected a plot based on the dot’s alignment on the highlighted plot on their screens. For example, one participant commented, “I feel like it’s probably wrong [plot], but it’s (the blue dot) lined up on the thing (the highlighted plot on their screen). But I just don't know if that's right, so we'll start here”. This participant did not change their strategy even when they were unsuccessful in their first task of the condition.

The strategy of *counting the plots* came with its own set of challenges for the participants; some participants made mistakes and miscounted. They used the highlighted plot as their reference point before starting the next task, but when the highlight would switch to the next plot for the next task, some participants forgot the location of their reference point on the map and thus could not correctly count the plots. This led to their counting being off by one or two plots. One participant said, “When you changed [the highlighted plot], I forgot what I was doing, like I was using the dot, but I said, ‘Okay, this time it’s going one or less than one.’ So when you changed the plot, it highlight one, right? So I always pointed with my finger where it was highlighted before. So then I count from that, but when you change it, I just lost my attention for a second and like ‘Where was it?’ Okay, the dot was one before, so I start counting from there. So I am at the wrong one because I forgot if the dot was one before or one after”. Some participants, however, were able to successfully count the plots by putting a finger or thumb on the highlighted plot and then when the highlight would change, they would treat their thumb location on a plot as a reference point and count correctly. One participant commented, “When you switched it (the highlighted plot), I put my thumb on the starting block, and then I counted from that using my thumb as the reference point”. Another comment stated, “As the accuracy got worse, I didn’t trust that dot as my starting point, so I was putting my finger over the blue plot and waiting for you to populate the next one”.

Some participants mentioned that they chose the target plots based on the shortest distance between the dot and any of the plots on their screen as they were walking past the plots on the ground that they were considering to be the choices for the correct plot. Specifically, they chose the plot which, when they walked past it, displayed the shortest on-screen distance from the dot. According to one participant, “If you seek the [difference in] distance between [the dot and the] two blocks [you are deciding between] and observe the dot, you can find the answer”.

Another type of location-finding strategy was used by participants who focused on the dot’s movements near the plots they were observing and used the overlapping location points to choose the target plot. A notable aspect of this strategy was that it was accompanied by the *counting the plots* strategy. These participants wanted to make sure they selected the correct plot, so they counted the plots beforehand and then carried out mental calculations for estimating an average location from the overlapping locations they observed once they were in the vicinity of the target plot. This combination of the two strategies indicates that the plot count was their backup (in case they failed the first attempt) or confirmation that their location approximations worked out. One participant explained their method of plot finding as, “In maybe the last 3 conditions, what I was doing is I would take a bunch of data points in front of the one I counted and say, ‘okay, here's my massive statistical points. I’m going to walk in front of the next one and then I’m going to see what it looks like.' And then I'd have kind of like figure 8 of spheres overlapping, and then I would walk over here and I would take that sphere of dots, and then based on which one had the most overlap with the one I counted, then I would know between these two [plots]. And then I would typically pick one I had counted."

Throughout the tasks with a significant level of error rate, participants depended heavily on *counting the plots*, either to make sure they selected the correct plot or to back up their location estimations if they could not find the plot successfully. Those who did not count or perform mental calculations and estimations to find the plots either were unsuccessful in finding the target plots or completed the tasks due to chance because the dot randomly landed on the correct plot and led them to select the correct corresponding plot on the ground, or they guessed the correct plot.

5.2.6 Change Towards Dot Behaviour

Participants' perception and behaviour towards the dot changed over time. Some participants who were doubtful of how the dot moved and whether it accurately displayed their location on the on-screen map with respect to their location during the tasks changed their views significantly when they started working on the tasks in lower accuracy conditions with increased error rates.

5.2.6.1 Dot's Alignment Along the Plot Edge

Some participants had such high expectations for the dot's location accuracy that they only considered the location to be correct if the dot was exactly at the location where they were standing. This analysis of the dot's location resulted in lower ratings for the dot's accuracy in the 0.0-metre and 0.85-metre error conditions. One participant pointed out that the "dot did not align with center of plot when I stood there" and gave a lower accuracy rating. Similar comments from the other participants in these first two experimental conditions were: "it was quite accurate but not exactly where I was standing", "pretty much in the middle but not exactly in the middle", and "accuracy means pinpoint and it's off".

However, once the participants began to experience error in the dot’s location in the later experimental conditions with higher error rates, they began to compare the current location accuracy of the dot with the location accuracy they had experienced in previous conditions. As a result, some participants began to give higher ratings to the dot’s accuracy if it helped them reach the correct plot. However, as expected, some participants lowered their ratings even further as the dot’s accuracy decreased with the increased error rate. One of the participants who gave a ten out of ten rating to the dot’s accuracy in the highest error rate condition stated that they did so “because it is showing the exact location. Even though it is far from the plot, it’s okay”.

5.2.6.2 Dot’s Accuracy During the Tasks

Some participants demonstrated a pragmatic understanding of the dot’s accuracy and stated that if they compared the study system’s map application with the map applications they used, it was accurate in depicting their correct location. They assessed the accuracy of the dot highly if the dot enabled them to find the target plots during the tasks. According to one participant, “the dot is very helpful as it shows whether you are standing at the edge of the next field, in the middle of the field or between two fields. This shows that the moving dot accurately provides your current location on the phone's interface”. Another participant commented, “I'm giving it 10 out of 10 because I find it (the plot) correctly. Because whenever we search for any location, we know the address, so if the dot indicates [a choice] between two places, we can select the right one”.

5.2.6.3 Reduced Dot Usage

During the initial experimental conditions, especially the first two, some of the participants relied less on the dot and rated its usage and usefulness lower, because they did not use the dot much or only referenced it a few times during their tasks, rather than because they found location discrepancies. This happened because they were generally aware of where they needed to go, i.e., they had to move either to the north or the south and, as a result, were able to move without constantly paying attention to the movements of the dot. As one participant said, “I haven’t used [the dot] a lot. It’s just general assistance, like I know where I am. I don't need to be too accurate

[as] I’m calculating the distance”. Another participant commented, “Based on the previous task, how far I walked, this time it was more distance, so I only watched it (the dot) three times and then saw it when I reached near to check if I have reached. So I didn’t use it much”.

5.2.6.4 Higher Ratings Based on the Ability to Find the Correct Plot

Some participants rated the subjective questionnaire measures higher if they were able to find the correct plot using the dot. They disregarded the error in the dot location as it did not interfere with their plot-finding process, and they were able to find the target plots. One participant remarked in the post-task feedback of the 2.975-metre error condition, “At the end of the day, I found the location based on the dot only”. Some participants also considered that their own movements and pace could affect the dot’s locations, not only interference or delays in the GPS signals. As a result, if they were able to find the target plot but the dot’s location on the on-screen map was not an accurate representation of their position in the field, they did not attribute this to the dot alone. This was expressed by one of the participants’ comments that “maybe it was my movements that caused the dot to maybe move, but as soon as I positioned myself, it showed me the right location” and rated the dot’s accuracy ten out of ten.

5.2.7 Learning Effects of Task Ordering

In the context of human-computer interaction (HCI), learning effects play a crucial role in user performance and experience with a particular system or task. Through repeated engagement in tasks over time, users gain experience, leading to improvements in various aspects such as task completion time, error reduction, problem-solving abilities, increased confidence, self-efficacy, and reduced cognitive effort.

All participants performed the study tasks in a consistent sequential order of error rates. Each experimental condition comprised two tasks, allowing participants to work with the same error rate in the dot's location for both tasks. This introduced some learning effects, where participants applied their knowledge gained from the condition's error rate in the first task to aid in completing the second task. Additionally, the sequential increase in error rates across experimental conditions provided participants with experience, helping them adjust to the location inaccuracy in the higher-error conditions.

The intentional sequential task order aimed to evaluate accuracy thresholds for carrying out location-finding tasks. To offset learning effects, the order of conditions could have been randomised. However, encountering higher error rates before lower ones would have significantly increased task difficulty, potentially hindering participants from completing the tasks. Despite the linear task ordering (from no error to higher error rates) and participants' practice and experience with tasks in lower-error rate conditions, their performance (Sections 4.5.1 and 4.5.2) and task experience (Sections 4.5.3 and 4.5.4) declined. This decline resulted from encountering better accuracy in earlier conditions, affecting their performance and subjective measures in subsequent experimental conditions.

These findings indicate that learning effects did not negatively impact the study results. Designing the study with a sequential task order proved to be the optimal approach for these tasks.

5.3 SUMMARY

This chapter discusses the various findings and observations of the two studies presented in the thesis. The results highlight the need to understand the effects of inaccuracy in location on users' trust in using the system's location elements such as the blue dot and the map applications. The results and user feedback indicate that user dependence on and use of location systems decrease significantly if the error in location is not easily interpretable by users. This leads to users resorting to other means of locating themselves or the objects of interest instead of using the intended location application.

CHAPTER 6

CONCLUSION

Mobile map applications are widely used by people to navigate and understand their surrounding environment. These apps effectively assist in various location-finding tasks, especially when the error margin in the location of the blue dot is significantly less than the size of the target, like a building, allowing for accurate identification. The online maps provide a real-world view, making it easy to align on-screen map views with the physical environment and determine location. However, challenges arise when the location-finding scenario demands high accuracy levels, approaching or equal to the size of the target. This situation is common in agricultural field research, where researchers must accurately locate specific plots in the field. Smaller plots, typically 1-2 m^2 rectangular regions arranged in rows and columns, require correct identification, making accuracy critical. The effects of reduced accuracy on user performance and behaviour, particularly when the error surpasses the target size, need thorough investigation to enhance the usability of such systems.

The accuracy of location information significantly impacts a user's ability to find a specific location in these scenarios. Investigating user behaviour when the accuracy falls below the target size is pivotal for developing effective solutions. This thesis presents the findings of two research studies focused on investigating smartphone GPS reliability for location-finding tasks in agricultural field research.

6.1 CONTRIBUTIONS

This thesis makes the following contributions:

The first study contributes to the identification of the factors influencing smartphone location accuracy and precision. It comprehensively explores location accuracy and precision under various network and location settings available on the testing device. The results of this study highlight that GPS provides relatively accurate and precise location readings when used in airplane mode, which preserves GPS sensor and receiver functionality. This knowledge opens up the possibility of utilising smartphones in agricultural field research work without the need for network connectivity, which is not always viable, especially in remote areas where network towers are not within proximate distance of the field sites.

The second study contributes valuable insights into the effects of reduced location accuracy on the user task of location-finding in an agricultural field research scenario. Participants performed plot identification tasks under six different experimental conditions, revealing the error thresholds that challenged their ability to perform the tasks. The study's findings indicate that when location error exceeds the target size, user performance declines, trust in the location information diminishes, and various strategies are employed to compensate for GPS inaccuracy.

The design of empirical studies and the research methods constitute the secondary contributions of this thesis. These elements of the research work can serve as methodological tools for investigating smartphone location accuracy, particularly in research domains where system accuracy faces challenges at threshold levels.

This thesis contributes new insights into smartphone GPS accuracy for location-finding in agricultural field research. The findings highlight that insufficient smartphone GPS accuracy negatively impacts user experience and trust in map applications. This research emphasizes the need to address the effects of GPS inaccuracy on user experience. The empirical evidence from the two studies can guide system designers and developers to better support users in challenging GPS conditions.

6.2 FUTURE WORK

For future extension of the research presented in this thesis, the following research directions are suggested:

The map view of the application interface was set to align with true north. Participants could rotate the map view as per their convenience and requirement. However, an alternative map view that automatically adjusts as participants change their direction and rotate their device can be implemented. This dynamic map view could benefit users struggling with orientation. Analysing their interactions with the map and how they utilise the blue dot's location information can offer insights into the impact of map view representation changes on user performance, especially considering the challenges of GPS inaccuracy.

The experimental conditions were introduced in a sequential order, progressing from no error to the highest error amount added to the dot location. Another viable approach would be to present the experimental conditions in a randomized order. This could help ascertain if users can interpret random error margins correctly and adapt to the system, even if a higher error amount experimental condition is introduced before a lower or no-error condition. Additionally, this approach could reveal any effects on user behaviour and their criteria for executing tasks in different experimental conditions with varying error amounts.

The error amount added to the location of the dot in each experimental condition was a fixed value. An alternative method to using the error amount in each condition could involve defining the error amount as the upper limit and allowing the error to be randomly added from a range of zero to the upper limit. In this implementation, the dot would not be consistently offset by the error amount with every location update, resulting in the probability of accurate location and minor error discrepancy with some of the location updates. This dot behaviour would closely resemble the location marker behaviour commonly encountered in map applications. Study 2 investigated different error rates in dot's location to understand how each error amount impacts user performance. Given the insights gained from the results, it is evident that inaccuracy significantly affects users' performance in location finding tasks. Therefore, investigating how setting the error rate as an upper limit instead of a fixed amount affects user performance and their experience with the map application and location information would be a valuable pursuit.

Experimenting with a range of angles of displacement from the true dot location is another avenue to explore. The study system introduced a random direction angle with every location update, ranging from 0° to 360°. Possible design variations concerning the angle could involve selecting a constant angle from this range and maintaining it throughout the trial, adjusting the range of selectable angles, or setting an upper limit for the angle within the range and varying it with each location update.

A subjective questionnaire was developed to assess participants' use of, trust in, perceived accuracy, and usefulness of the blue dot during the tasks. To accommodate the study's time constraints, the NASA-TLX, a standardized subjective workload questionnaire, was employed after each experimental condition. Additionally, validated standardised questionnaires could be used for a more comprehensive evaluation of these measures.

Landmarks could be used to assist participants with location-finding in higher-error conditions. Introducing landmarks in the field and incorporating them into the map interface can assist participants in reaching the general area of the target plot more efficiently. To simulate the agricultural field environment, Study 2 employed a terrain view of the map in the client-mode application interface. However, landmarks have the potential to reduce both task completion time and user error count, particularly in higher error conditions. The incorporation of landmarks in the study design can also align with the user strategy of *counting the plots*, as they would only need to count a limited number of plots within the target plot's vicinity. This can enhance user performance in location-finding tasks.

These future directions could yield additional insights into user behaviour and the impact of decreased location accuracy on users and their experience with smartphone map applications for location-finding tasks. This deeper understanding can inform the enhancement of systems for users of location-based applications.

6.3 SUMMARY

Mobile map applications are a fundamental part of everyday navigation for people. The reliance on these apps highlights their potential for application in work domains with specific accuracy requirements. To provide convenient and reliable solutions for agricultural field research, it is crucial to establish a foundation that elucidates the capabilities and limitations of current state-of-the-art GPS systems on smartphones. The research conducted in this thesis addresses this need, shedding light on the effects of reduced accuracy on user tasks of location-finding and the various alternative strategies employed to compensate for the lack of accurate location information. The two studies provide empirical evidence regarding smartphone GPS location information, contributing to an understanding of how users utilise location information, interact with the system, perceive the location accuracy, and form expectations regarding the system's usefulness and accuracy. Furthermore, the findings highlight how user behaviour and performance changes over time due to different levels of accuracy.

REFERENCES

1. Arturo Aquino, Ignacio Barrio, Maria-Paz Diago, Borja Millan, and Javier Tardaguila. 2018. vitisBerry: An Android-smartphone application to early evaluate the number of grapevine berries by means of image analysis. *Computers and Electronics in Agriculture* 148: 19–28.

2. Simon Banville and Frank van Diggelen. 2016. Precision GNSS for everyone. *GPS World* 27, 11: 43–48.

3. F C Bârliba, I C Gheorghescu, and Anca-Maria Moscovici. 2017. The advantages of using mobile GIS technology. *Research Journal of Agricultural Science* 49, 4: 20–28.

4. Jan Bauer, Bastian Siegmann, Thomas Jarmer, and Nils Aschenbruck. 2016. Smart fLAIr: A smartphone application for fast LAI retrieval using ambient light sensors. In *2016 IEEE sensors applications symposium (SAS)*, 1–6.

5. Roberta De Bei, Sigfredo Fuentes, Matthew Gilliham, Steve Tyerman, Everard Edwards, Nicolò Bianchini, Jason Smith, and Cassandra Collins. 2016. VitiCanopy: A free computer App to estimate canopy vigor and porosity for grapevine. *Sensors* 16, 4: 585.

6. Dror Ben-Zeev, Emily A Scherer, Rui Wang, Haiyi Xie, and Andrew T Campbell. 2015. Next-generation psychiatric assessment: Using smartphone sensors to monitor behavior and mental health. *Psychiatric rehabilitation journal* 38, 3: 218.

7. Norman Bonnor. 2012. A brief history of global navigation satellite systems. *The Journal of Navigation* 65, 1: 1–14.

8. Jere A Boudell and Beth A Middleton. 2019. Plot Locator: An app for locating plots in the field. *Applications in plant sciences* 7, 12: e11311.

9. Michael S Braasch. 2017. Multipath. *Springer handbook of global navigation satellite systems*: 443–468.

10. Virginia Braun and Victoria Clarke. 2006. Using thematic analysis in psychology. *Qualitative research in psychology* 3, 2: 77–101.

11. M Victoria Bueno-Delgado, José Miguel Molina-Martínez, R Correoso-Campillo, and Pablo Pavón-Mariño. 2016. Ecofert: An Android application for the optimization of fertilizer cost in fertigation. *Computers and Electronics in Agriculture* 121: 32–42.

12. Hilary F Byrnes, Brenda A Miller, Christopher N Morrison, Douglas J Wiebe, Lillian G Remer, and Sarah E Wiehe. 2016. Brief report: Using global positioning system (GPS) enabled cell phones to examine adolescent travel patterns and time in proximity to alcohol outlets. *Journal of Adolescence* 50: 65–68.

13. Wu Caicong, Zhou Lin, Wang Jie, and Cai Yaping. 2016. Smartphone based precise monitoring method for farm operation. *International Journal of Agricultural and Biological Engineering* 9, 3: 111–121.

14. Kathleen Carley. 1990. Content analysis.

15. Pietro Catania, Antonio Comparetti, Pierluigi Febo, Giuseppe Morello, Santo Orlando, Eliseo Roma, and Mariangela Vallone. 2020. Positioning accuracy comparison of GNSS receivers used for mapping and guidance of agricultural machines. *Agronomy* 10, 7: 924.

16. Adam Ciećko. 2019. Analysis of the EGNOS quality parameters during high ionosphere activity. *IET Radar, Sonar & Navigation* 13, 7: 1131–1139.

17. Jacob Cohen. 1973. Eta-squared and partial eta-squared in fixed factor ANOVA designs. *Educational and psychological measurement* 33, 1: 107–112.

18. Paolo Dabove and Vincenzo Di Pietra. 2019. Towards high accuracy GNSS real-time positioning with smartphones. *Advances in Space Research* 63, 1: 94–102.

19. Nils Dahlbäck, Arne Jönsson, and Lars Ahrenberg. 1993. Wizard of Oz studies: why and how. In *Proceedings of the 1st international conference on Intelligent user interfaces*, 193–200.

20. Gino Dardanelli, Antonino Maltese, Claudia Pipitone, Alessandro Pisciotta, and Mauro Lo Brutto. 2021. NRTK, PPP or static, that is the question. Testing different positioning solutions for GNSS survey. *Remote Sensing* 13, 7: 1406.

21. Department Of Defense USA. 2020. Global Positioning System Standard Positioning Service Performance Standard. *www.Gps.Gov*, 5th Edition: 1–196. https://www.gps.gov/technical/ps/

22. Frank Stephen Tromp Van Diggelen. 2009. *A-gps: Assisted gps, gnss, and sbas*. Artech house.

23. Frank van Diggelen. 2020. High-Sensitivity GNSS. *Position, navigation, and timing technologies in the 21st century: Integrated satellite navigation, sensor systems, and civil applications* 1: 445–479.

24. Frank van Diggelen. 2020. Assisted GNSS. *Position, Navigation, and Timing Technologies in the 21st Century: Integrated Satellite Navigation, Sensor Systems, and Civil Applications* 1: 419–444.

25. Frank Van Diggelen and Per Enge. 2015. The world's first GPS MOOC and worldwide laboratory using smartphones. In *Proceedings of the 28th international technical meeting of the satellite division of the institute of navigation (ION GNSS+ 2015)*, 361–369.

26. Davis Dinkov and Atanas Kitev. 2020. Advantages, disadvantages and applicability of GNSS post-processing kinematic (PPK) method for direct georeferencing of UAV images. In *Proceedings of the 8th International Conference on Cartography and GIS, Nessebar, Bulgaria*, 15–20.

27. Daniel Egea-Roca, Markel Arizabaleta-Diez, Thomas Pany, Felix Antreich, José A López-Salcedo, Matteo Paonni, and Gonzalo Seco-Granados. 2022. GNSS user technology: State-of-the-art and future trends. *IEEE Access* 10: 39939–39968.

28. Bernd Eissfeller and Jong-Hoon Won. 2017. Receiver Architecture. *Springer Handbook of Global Navigation Satellite Systems*: 365–400.

29. Lisa A Elkin, Matthew Kay, James J Higgins, and Jacob O Wobbrock. 2021. An aligned rank transform procedure for multifactor contrast tests. In *The 34th annual ACM symposium on user interface software and technology*, 754–768.

30. Abdelsatar Elmezayen and Ahmed El-Rabbany. 2019. Precise point positioning using world's first dual-frequency GPS/GALILEO smartphone. *Sensors* 19, 11: 2593.

31. J Connor Ferguson, Rodolfo G Chechetto, Chris C O'Donnell, Brad K Fritz, W Clint Hoffmann, Chet E Coleman, Bhagirath S Chauhan, Steve W Adkins, Greg R Kruger, and Andrew J Hewitt. 2016. Assessing a novel smartphone application–SnapCard, compared to five imaging systems to quantify droplet deposition on artificial collectors. *Computers and Electronics in Agriculture* 128: 193–198.

32. G García-Mateos, J L Hernández-Hernández, D Escarabajal-Henarejos, S Jaén-Terrones, and J M Molina-Martínez. 2015. Study and comparison of color models for automatic image analysis in irrigation management applications. *Agricultural water management* 151: 158–166.

33. M GOODMAN and S JACQUES. 2000. Civilian benefits of discontinuing selective availability. Commerce News, United Sates Department of Commerce from 01.05. 2000. *URL: http://www. igeb. gov/sa/benefits. shtml*.

34. Robert Goodspeed, Xiang Yan, Jean Hardy, V G Vinod Vydiswaran, Veronica J Berrocal, Philippa Clarke, Daniel M Romero, Iris N Gomez-Lopez, and Tiffany Veinot. 2018. Comparing the data quality of global positioning system devices and mobile phones for assessing relationships between place, mobility, and health: field study. *JMIR mHealth and uHealth* 6, 8: e9771.

35. Ben Grayson, Nigel T Penna, Jon P Mills, and Darion S Grant. 2018. GPS precise point positioning for UAV photogrammetry. *The photogrammetric record* 33, 164: 427–447.

36. Gabriella M Harari, Nicholas D Lane, Rui Wang, Benjamin S Crosier, Andrew T Campbell, and Samuel D Gosling. 2016. Using smartphones to collect behavioral data in psychological science: Opportunities, practical considerations, and challenges. *Perspectives on Psychological Science* 11, 6: 838–854.

37. Anne Hardy, Sarah Hyslop, Kate Booth, Brady Robards, Jagannath Aryal, Ulrike Gretzel, and Richard Eccleston. 2017. Tracking tourists' travel with smartphone-based GPS technology: a methodological discussion. *Information Technology & Tourism* 17: 255–274.

38. Sandra G Hart and Lowell E Staveland. 1988. Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. In *Advances in psychology*. Elsevier, 139–183.

39. Will Hedgecock, Miklos Maroti, Janos Sallai, Peter Volgyesi, and Akos Ledeczi. 2013. High-accuracy differential tracking of low-cost GPS receivers. In *Proceeding of the 11th annual international conference on Mobile systems, applications, and services*, 221–234.

40. Christopher J. Hegarty. 2017. The Global Positioning System (GPS). *Springer Handbooks*: 197–218. https://doi.org/10.1007/978-3-319-42928-1_7/COVER

41. J L Hernández-Hernández, J Ruiz-Hernández, G García-Mateos, J M González-Esquiva, A Ruiz-Canales, and J M Molina-Martínez. 2017. A new portable application for automatic segmentation of plants in agriculture. *Agricultural water management* 183: 146–157.

42. Shengyue Ji, Wu Chen, Xiaoli Ding, Yongqi Chen, Chunmei Zhao, and Congwei Hu. 2010. Potential benefits of GPS/GLONASS/GALILEO integration in an urban canyon–Hong Kong. *The Journal of Navigation* 63, 4: 681–693.

43. Shuanggen Jin, Qisheng Wang, and Gino Dardanelli. 2022. A review on multi-GNSS for earth observation and emerging applications. *Remote Sensing* 14, 16: 3930.

44. Walter Maldonado Júnior, Taynara Tuany Borges Valeriano, and Glauco de Souza Rolim. 2019. EVAPO: A smartphone application to estimate potential evapotranspiration using

cloud gridded meteorological data from NASA-POWER system. *Computers and Electronics in Agriculture* 156: 187–192.

45. Elliott D Kaplan and Christopher Hegarty. 2017. *Understanding GPS/GNSS: principles and applications*. Artech house.

46. Malek Karaim, Mohamed Elsheikh, Aboelmagd Noureldin, and R B Rustamov. 2018. GNSS error sources. *Multifunctional Operation and Application of GPS*: 69–85.

47. Anna Klimaszewski-Patterson. 2010. Smartphones in the field: preliminary study comparing GPS capabilities between a smartphone and dedicated GPS device. In *Applied Geography Conferences*, 270–279.

48. Silviya Korpilo, Tarmo Virtanen, and Susanna Lehvävirta. 2017. Smartphone GPS tracking—Inexpensive and efficient data collection on recreational movement. *Landscape and Urban Planning* 157: 608–617.

49. K Krzykowska, M Siergiejczyk, and A Rosiński. 2018. Influence of selected external factors on satellite navigation signal quality. 701–705.

50. Karolina Krzykowska-Piotrowska, Ewa Dudek, Paweł Wielgosz, Beata Milanowska, and Jordi Mongay Batalla. 2021. On the Correlation of Solar Activity and Troposphere on the GNSS/EGNOS Integrity. Fuzzy Logic Approach. *Energies* 14, 15: 4534.

51. Richard B Langley, Peter J G Teunissen, and Oliver Montenbruck. 2017. Introduction to GNSS. *Springer handbook of global navigation satellite systems*: 3–23.

52. Jérôme Leclère, René Landry Jr, and Cyril Botteron. 2018. Comparison of L1 and L5 bands GNSS signals acquisition. *Sensors* 18, 9: 2779.

53. Xianghong Li, Dongyan Wei, Qifeng Lai, Ying Xu, and Hong Yuan. 2017. Smartphone-based integrated PDR/GPS/Bluetooth pedestrian location. *Advances in Space Research* 59, 3: 877–887.

54. Xingxing Li, Xiaohong Zhang, Xiaodong Ren, Mathias Fritsche, Jens Wickert, and Harald Schuh. 2015. Precise positioning with current multi-constellation global navigation satellite systems: GPS, GLONASS, Galileo and BeiDou. *Scientific reports* 5, 1: 8328.

55. Bruno Brandoli Machado, Jonatan P M Orue, Mauro S Arruda, Cleidimar V Santos, Diogo S Sarath, Wesley N Goncalves, Gercina G Silva, Hemerson Pistori, Antonia Railda Roel, and Jose F Rodrigues-Jr. 2016. BioLeaf: A professional mobile application to measure foliar damage caused by insect herbivory. *Computers and electronics in agriculture* 129: 44–55.

56. Bruno Brandoli Machado, Gabriel Spadon, Mauro S Arruda, Wesley N Goncalves, Andre CPLF Carvalho, and Jose F Rodrigues-Jr. 2018. A smartphone application to measure the quality of pest control spraying machines via image analysis. In *Proceedings of the 33rd Annual ACM Symposium on Applied Computing*, 956–963.

57. Krista Merry and Pete Bettinger. 2019. Smartphone GPS accuracy study in an urban environment. *PloS one* 14, 7: e0219890.

58. Kati W Migliaccio, K T Morgan, C Fraisse, George Vellidis, and J H Andreis. 2015. Performance evaluation of urban turf irrigation smartphone app. *Computers and Electronics in Agriculture* 118: 136–142.

59. Y Jade Morton, Frank van Diggelen, James J Spilker Jr, Bradford W Parkinson, Sherman Lo, and Grace Gao. 2021. *Position, navigation, and timing technologies in the 21st century: Integrated satellite navigation, sensor systems, and civil applications, volume 1*. John Wiley & Sons.

60. Mohamed Z Mostafa, Hatem A Khater, Mohamed R Rizk, and Abdullah M Bahasan. 2019. A novel GPS/RAVO/MEMS-INS smartphone-sensor-integrated method to enhance USV navigation systems during GPS outages. *Measurement Science and Technology* 30, 9: 095103.

61. Maciej Nowakowski, Ewa Dudek, and Adam Rosiński. 2023. The Influence of Varying Atmospheric and Space Weather Conditions on the Accuracy of Position Determination. *Sensors 2023, Vol. 23, Page 2814* 23, 5: 2814. https://doi.org/10.3390/S23052814

62. Robert Odolinski and Peter J G Teunissen. 2019. An assessment of smartphone and low-cost multi-GNSS single-frequency RTK positioning for low, medium and high ionospheric disturbance periods. *Journal of Geodesy* 93, 5: 701–722.

63. Kristen Olson and James Wagner. 2015. A feasibility test of using smartphones to collect GPS information in face-to-face surveys.

64. Barrett O'neill. 2006. *Elementary differential geometry*. Elsevier.

65. Francesca Orlando, Ermes Movedi, Davide Coduto, Simone Parisi, Lucio Brancadoro, Valentina Pagani, Tommaso Guarneri, and Roberto Confalonieri. 2016. Estimating leaf area index (LAI) in vineyards using the PocketLAI smart-app. *Sensors* 16, 12: 2004.

66. Bradford W Parkinson and James J Spilker. 1996. *Progress in astronautics and aeronautics: Global positioning system: Theory and applications*. Aiaa.

67. Jacek Paziewski. 2020. Recent advances and perspectives for positioning and applications with smartphone GNSS observations. *Measurement Science and Technology* 31, 9: 091001.

68. Jacek Paziewski, Marco Fortunato, Augusto Mazzoni, and Robert Odolinski. 2021. An analysis of multi-GNSS observations tracked by recent Android smartphones and smartphone-only relative positioning results. *Measurement* 175: 109162.

69. Félix Perosanz. 2019. GNSS: A revolution for precise geopositioning. *Comptes Rendus Physique* 20, 3: 171–175.

70. Nikos Petrellis. 2018. A Smart Phone Image Processing Application for Plant Disease Diagnosis. June. https://doi.org/10.1109/MOCAST.2017.7937683

71. Nikos Petrellis. 2019. Plant disease diagnosis for smart phone applications with extensible set of diseases. *Applied Sciences* 9, 9: 1952.

72. Paul R Petrie, Yeniu Wang, Scarlett Liu, Stanley Lam, Mark A Whitty, and Mark A Skewes. 2019. The accuracy and utility of a low cost thermal camera and smartphone-based system to assess grapevine water status. *Biosystems Engineering* 179: 126–139.

73. Atınç Pırtı. 2021. Evaluating the accuracy of post-processed kinematic (Ppk) positioning technique. *Geodesy and Cartography* 47, 2: 66–70.

74. Suporn Pongnumkul, Pimwadee Chaovalit, and Navaporn Surasvadi. 2015. Applications of smartphone-based sensors in agriculture: a systematic review of research. *Journal of Sensors* 2015.

75. National Space-based Positioning and Timing Advisory Board. 2023. White Paper - GPS High Accuracy and Robustness Service (HARS).

76. Umberto Robustelli, Jacek Paziewski, and Giovanni Pugliano. 2021. Observation quality assessment and performance of GNSS standalone positioning with code pseudoranges of dual-frequency Android smartphones. *Sensors* 21, 6: 2125.

77. Stanisław Rosłoniec. 2023. *Fundamentals of the radiolocation and radionavigation*. Springer.

78. Angela Rout, Sophie Nitoslawski, Andrew Ladle, and Paul Galpern. 2021. Using smartphone-GPS data to understand pedestrian-scale behavior in urban settings: A review of themes and approaches. *Computers, Environment and Urban Systems* 90: 101705.

79. Rustam B Rustamov and Arif M Hashimov. 2018. *Multifunctional Operation and Application of GPS*. BoD–Books on Demand.

80. Mariusz Rychlicki, Zbigniew Kasprzyk, and Adam Rosiński. 2020. Analysis of accuracy and reliability of different types of GPS receivers. *Sensors* 20, 22: 6498.

81. Ahmed Sheta, Ahmed Mohsen, Bassem Sheta, and Mohamed Hassan. 2018. Improved localization for Android smartphones based on integration of raw GNSS measurements and IMU sensors. In *2018 International conference on computer and applications (ICCA)*, 297–302.

82. Stefan Steiniger, Moritz Neun, and Alistair Edwardes. 2006. Foundations of location based services. *Lecture Notes on LBS* 1, 272: 2.

83. Steven E Stemler. 2015. Content analysis. *Emerging trends in the social and behavioral sciences: An Interdisciplinary, Searchable, and Linkable Resource*: 1–14.

84. Roxanne Stiglitz, Elena Mikhailova, Christopher Post, Mark Schlautman, Julia Sharp, Roy Pargas, Benjamin Glover, and Jack Mooney. 2017. Soil color sensor data collection using a GPS-enabled smartphone application. *Geoderma* 296: 108–114.

85. Timothy Stombaugh. 2018. Satellite-based Positioning Systems for Precision Agriculture. *Precision agriculture basics*: 25–35.

86. Li Nyen Thin, Lau Ying Ting, Nor Adila Husna, and Mohd Heikal Husin. 2016. GPS systems literature: inaccuracy factors and effective solutions. *International Journal of Computer Networks & Communications (IJCNC)* 8, 2: 123–131.

87. Julián Tomaštík Jr, Julián Tomaštík Sr, Šimon Saloň, and Rastislav Piroh. 2017. Horizontal accuracy and applicability of smartphone GNSS positioning in forests. *Forestry: An International Journal of Forest Research* 90, 2: 187–198.

88. Minh Tran. 2015. Accurate Location Detection--911 Help SMS App.

89. Tarık Türk, Nursu Tunalioglu, Bahattin Erdogan, Taylan Ocalan, and Mert Gurturk. 2022. Accuracy assessment of UAV-post-processing kinematic (PPK) and UAV-traditional (with ground control points) georeferencing methods. *Environmental Monitoring and Assessment* 194, 7: 476.

90. George Vellidis, Vasileios Liakos, J H Andreis, C D Perry, W M Porter, E M Barnes, K T Morgan, Clyde Fraisse, and Kati W Migliaccio. 2016. Development and assessment of a smartphone application for irrigation scheduling in cotton. *Computers and Electronics in Agriculture* 127: 249–259.

91. Zhenglin Wang, Anand Koirala, Kerry Walsh, Nicholas Anderson, and Brijesh Verma. 2018. In field fruit sizing using a smart phone application. *Sensors* 18, 10: 3331.

92. René Warnant, De Vyvere, Laura Van, and Quentin Warnant. 2018. Positioning with single and dual frequency smartphones running Android 7 or later. In *Proceedings of the 31st international technical meeting of the satellite division of the Institute of Navigation (ION GNSS+ 2018)*, 284–303.

93. Jacob O Wobbrock, Leah Findlater, Darren Gergle, and James J Higgins. 2011. The aligned rank transform for nonparametric factorial analyses using only anova procedures. In *Proceedings of the SIGCHI conference on human factors in computing systems*, 143–146.

94. Wenlin Yan, Luísa Bastos, and Américo Magalhães. 2019. Performance assessment of the android smartphone's IMU in a GNSS/INS coupled navigation model. *IEEE Access* 7: 171073–171083.

95. Erin York Cornwell and Kathleen A Cagney. 2017. Aging in activity space: results from smartphone-based GPS-tracking of urban seniors. *Journals of Gerontology Series B: Psychological Sciences and Social Sciences* 72, 5: 864–875.

96. He Zhang, Emilien Aldana-Jague, François Clapuyt, Florian Wilken, Veerle Vanacker, and Kristof Van Oost. 2019. Evaluating the potential of post-processing kinematic (PPK) georeferencing for UAV-based structure-from-motion (SfM) photogrammetry and surface change detection. *Earth Surface Dynamics* 7, 3: 807–827.

97. Camera and view | Maps SDK for Android | Google for Developers. https://developers.google.com/maps/documentation/android-sdk/views#introduction

98. Explore Street View and add your own 360 images to Google Maps. https://www.google.ca/streetview/

99. Google I/O Preview: Introducing new 3D imagery, map customization, and routing products | Google Cloud Blog. https://cloud.google.com/blog/products/maps-platform/google-io-preview-introducing-new-3d-imagery-map-customization-and-routing-products

100. About – Google Maps. https://www.google.com/maps/about/#!/

101. Maps - Apple (CA). https://www.apple.com/ca/maps/

102. Driving directions, live traffic & road conditions updates - Waze. https://www.waze.com/live-map/

103. How Does Location Work: Sources of location data (GPS, Wifi, Cell Tower Triangulation) – GroundTruth Help Center. https://help.groundtruth.com/hc/en-us/articles/360000709047-How-Does-Location-Work-Sources-of-location-data-GPS-Wifi-Cell-Tower-Triangulation-

104. GPS.gov: GPS Accuracy. https://www.gps.gov/systems/gps/performance/accuracy/

105. GPS.gov: Space Segment. https://www.gps.gov/systems/gps/space/

106. GPS Performances - Navipedia.https://gssc.esa.int/navipedia/index.php/GPS_Performances

107. Brief History of GPS | The Aerospace Corporation. https://aerospace.org/article/brief-history-gps

108. Find & improve your location’s accuracy - Android - Google Maps Help. https://support.google.com/maps/answer/2839911?hl=en&co=GENIE.Platform%3DAndroid#zippy=%2Ccalibrate-your-phone-or-tablet