Journal of Computer and Communications, 2024, 12, 39-62
https://www.scirp.org/journal/jcc
ISSN Online: 2327-5227
ISSN Print: 2327-5219

Evaluating Global Navigation Satellite System (GNSS) Constellation Performance for Unmanned Aerial Vehicle (UAV) Navigation Precision

Ahad Alotaibi, Chris Chatwin, Phil Birch

Department of Engineering and Design, School of Engineering and Informatics, University of Sussex, Brighton, UK
Email: aa2758@sussex.ac.uk

How to cite this paper: Alotaibi, A., Chatwin, C. and Birch, P. (2024) Evaluating Global Navigation Satellite System (GNSS) Constellation Performance for Unmanned Aerial Vehicle (UAV) Navigation Precision. *Journal of Computer and Communications*, **12**, 39-62.
https://doi.org/10.4236/jcc.2024.129003

Received: August 19, 2024
Accepted: September 10, 2024
Published: September 13, 2024

Abstract

Accurate localization is paramount for unmanned aerial vehicles (UAVs) spanning various technical and industrial domains, necessitating a comprehensive assessment of global navigation satellite system (GNSS) precision. This study investigates the performance of distinct GNSS constellations in determining the precise location of a building utilizing a high-precision GNSS receiver. The receiver, incorporating advanced multi-frequency and full-constellation positioning capabilities, was integrated with a smartphone via Bluetooth to enable the UAV's acquisition of centimeter-level positioning data. Sequential utilization of single satellite systems—such as GPS-only, GLONASS-only, Galileo-only, SBAS-only, and BeiDou-only—facilitated the documentation of latitude and longitude coordinates for the designated building. Subsequent comparison of these coordinates with a specialized Geographic Information System (GIS) was conducted to evaluate their positional accuracy. The comparative analysis underscores significant variability in the precision offered by each satellite constellation, providing valuable insights for optimizing UAV navigation across GIS, IoT, construction, and other sectors requiring high-precision localization. This research underscores the significance of high-precision GNSS receivers in enhancing UAV-based geospatial assessments, emphasizing the critical selection of appropriate satellite systems for tailored localization tasks. The study contributes to advancing UAV navigation strategies, ensuring robust and accurate geospatial data collection within diverse operational frameworks.

Keywords

UAV, GNSS, Localization, Precision, Comparative, GIS

1. Introduction

Unmanned aerial vehicles (UAVs), commonly known as drones, have become integral tools in geospatial science, revolutionizing the way buildings are located, mapped, and analyzed, alongside numerous other applications related to geographic information systems (GIS). UAVs equipped with advanced sensors and high-resolution cameras capture detailed aerial imagery and data, enabling precise and efficient mapping of urban and rural environments. In the context of locating buildings, UAVs offer unparalleled capabilities for surveying and documenting structures with high accuracy. They can fly at various altitudes, capturing images that can be processed into detailed orthomosaic maps and 3D models, which are invaluable for urban planning, architecture, and construction, allowing professionals to visualize and assess the built environment comprehensively [1]. UAVs enhance the efficiency of building location tasks by reducing the time and labor traditionally required for ground-based surveys. For instance, in urban development projects, drones can quickly map large areas, providing up-to-date geospatial data that reflects current conditions. This real-time data acquisition is crucial for monitoring construction progress, verifying site conditions, and ensuring compliance with design specifications. By integrating UAV-captured data into GIS, planners and engineers can perform spatial analyses, identify potential issues, and make informed decisions based on accurate, high-resolution maps [2]. In addition to locating and mapping buildings, UAVs are extensively used in various GIS applications, such as land surveying, environmental monitoring, and infrastructure management. In land surveying, drones equipped with LiDAR (Light Detection and Ranging) sensors create precise topographic maps, capturing fine details of the terrain essential for land use planning, property delineation, and resource management. The ability of UAVs to quickly cover large areas and generate detailed elevation models makes them indispensable for geospatial professionals [3]. Environmental monitoring is another critical application where UAVs have a significant impact. Drones can monitor changes in land use, vegetation health, and natural habitats, providing data vital for conservation efforts and environmental protection. For example, in forest management, UAVs assess tree health, detect illegal logging activities, and monitor reforestation projects. This capability enhances the ability of environmental agencies to manage natural resources sustainably and respond promptly to ecological threats [4].

In infrastructure management, UAVs offer substantial benefits for inspecting and maintaining critical assets such as roads, bridges, power lines, and pipelines. Equipped with high-resolution cameras and thermal sensors, drones can identify structural defects, assess damage, and monitor the condition of infrastructure components without the need for manual inspections. This not only improves safety by reducing the need for personnel to access hazardous areas but also enhances the efficiency and accuracy of maintenance operations [5].

UAVs also play a pivotal role in disaster management and emergency response. In the aftermath of natural disasters such as earthquakes, floods, and hurricanes, drones can quickly survey affected areas, providing real-time imagery and data to emergency responders. This rapid assessment capability is crucial for coordinating relief efforts, identifying safe routes for rescue operations, and assessing damage to infrastructure. UAVs can also create detailed maps of disaster-stricken areas, aiding in the planning and execution of recovery and reconstruction activities [6]. The integration of UAV data into GIS platforms further amplifies the value of drone technology in geospatial applications. GIS software can process and analyze UAV-captured data, generating insights that inform decision-making across various sectors. For instance, in urban planning, GIS can combine drone imagery with other spatial data layers to evaluate land use patterns, plan new developments, and optimize the placement of public facilities. In agriculture, GIS can analyze UAV data to monitor crop health, predict yields, and manage irrigation more effectively [7]. Moreover, UAVs are increasingly used for photogrammetry, a technique that involves capturing overlapping aerial photographs to create accurate 3D models of the terrain and built environment. These 3D models are essential for a wide range of applications, from virtual city tours and heritage preservation to infrastructure planning and environmental impact assessments. Photogrammetry allows for the creation of digital twins—virtual replicas of physical assets—that can be used for simulation, analysis, and visualization purposes [8].

Satellites play a pivotal role in modern navigation, providing the foundational infrastructure for global navigation satellite systems (GNSS) such as Global Positioning System (GPS), GLObalnaya NAvigatsionnaya Sputnikovaya Sistema (GLONASS), Galileo, and BeiDou. These systems are essential for determining precise location coordinates anywhere on Earth, which is crucial for a wide range of applications, from everyday navigation in smartphones to advanced geospatial analyses. Satellites transmit signals that are received by GNSS devices, allowing for the calculation of accurate positioning data through triangulation methods. This satellite-based navigation is indispensable for UAV operations, where precise location data is necessary for tasks such as mapping, surveying, and monitoring. The integration of GNSS with UAVs enhances their ability to perform high-precision geospatial tasks, enabling drones to capture detailed imagery and create accurate maps and 3D models. For example, when UAVs are used to locate and document buildings, the positional accuracy provided by GNSS ensures that the data collected is reliable and precise, which is crucial for urban planning, construction monitoring, and infrastructure inspection [9]. Moreover, GNSS-enabled UAVs can operate in various environments, including remote and inaccessible areas, providing critical data for environmental monitoring and disaster management. This synergy between satellite navigation and UAV technology underscores the transformative impact of GNSS on geospatial science, facilitating a multitude of applications that rely on accurate and timely geospatial data [10].

Building on the foundational role of GNSS in UAV applications, our experiment sought to evaluate the accuracy of various satellite systems in geospatial localization tasks using a high-precision GNSS receiver integrated with a UAV.

The experiment involved systematically testing different GNSS constellations—specifically GPS-only, GLONASS-only, Galileo-only, SBAS-only, and BeiDou-only—to determine their respective accuracies in pinpointing the location of a specific building. This was achieved by connecting the GNSS receiver to a smartphone via Bluetooth, which in turn controlled the UAV's navigation and data collection processes. The methodology entailed flying the UAV over the targeted building, with each flight dedicated to a single satellite system. During each flight, the GNSS receiver collected latitude and longitude coordinates of the building's location. These coordinates were then compared against a reference dataset obtained from a specialized Geographic Information System (GIS), known for its high accuracy and reliability. This comparative analysis aimed to identify which satellite system provided the most precise localization data under identical conditions.

Initial results indicated notable differences in the accuracy of the coordinates derived from each GNSS constellation. For instance, GPS-only data generally provided robust accuracy, aligning closely with the GIS reference points. Similarly, Galileo-only and BeiDou-only systems also demonstrated high levels of precision, albeit with minor variations influenced by satellite geometry and signal quality at the time of data capture. On the other hand, GLONASS-only and SBAS-only systems exhibited slightly lower accuracy, highlighting the variability inherent in different GNSS technologies.

These findings underscore the novelty of this study, which lies in its comprehensive comparative analysis of different GNSS constellations for UAV-based geospatial applications. By systematically evaluating the performance of each constellation, this research provides crucial insights into the optimal selection of GNSS systems based on specific operational requirements. The primary aim of this work is to enhance the precision and reliability of UAV operations in various fields such as urban planning, construction monitoring, and environmental surveying. These findings have significant implications for the deployment of UAVs in geospatial applications. The experiment underscores the importance of selecting the appropriate GNSS constellation based on the specific requirements of the task at hand, whether it be urban planning, construction monitoring, or environmental surveying. By leveraging the most accurate satellite systems, UAV operations can achieve higher precision in data collection, leading to better-informed decision-making processes in various fields. Furthermore, the integration of high-precision GNSS receivers with UAVs, coupled with the ability to switch between different satellite systems, provides a versatile platform for geospatial professionals. This flexibility enhances the capability of UAVs to operate in diverse environments and conditions, ensuring reliable and accurate geospatial data acquisition. As UAV technology continues to evolve, incorporating advancements in GNSS and other navigational aids, their applications in GIS and related domains are poised to expand, driving innovation and efficiency in geospatial sciences [11] [12].

2. Materials and Methods

2.1. SinoGNSS Z30 GNSS Receiver

The SinoGNSS Z30 GNSS receiver is a cutting-edge, high-precision device developed by ComNav Technology Ltd. It is designed for robust performance in a variety of demanding environments and applications. The Z30 is engineered to track full GNSS constellations, including GPS, GLONASS, Galileo, and BeiDou, providing users with reliable and highly accurate positioning data from sub-meter to centimeter level. This advanced receiver supports multi-frequency signals, which significantly enhance its positioning accuracy and reliability in challenging conditions such as urban canyons and dense foliage [13]. **Table 1** below shows the signals tracked by this receiver:

Table 1. Signals tracked by the receiver.

Satellites	Channels
GPS	L1 C/A, L1C, L2C, L2P, L5
BeiDou	B1l, B2l, B3l, B1C, B2a, B2b
GLONASS	G1, G2, G3
GALILEO	E1, E5a, E5b, E6c, E5 AltBOC
QZSS	L1C/A, L2C, L5, L1C
IRNSS	L5
SBAS	WAAS, EGNOS, MSAS, GAGAN,SDCM,BDSBAS

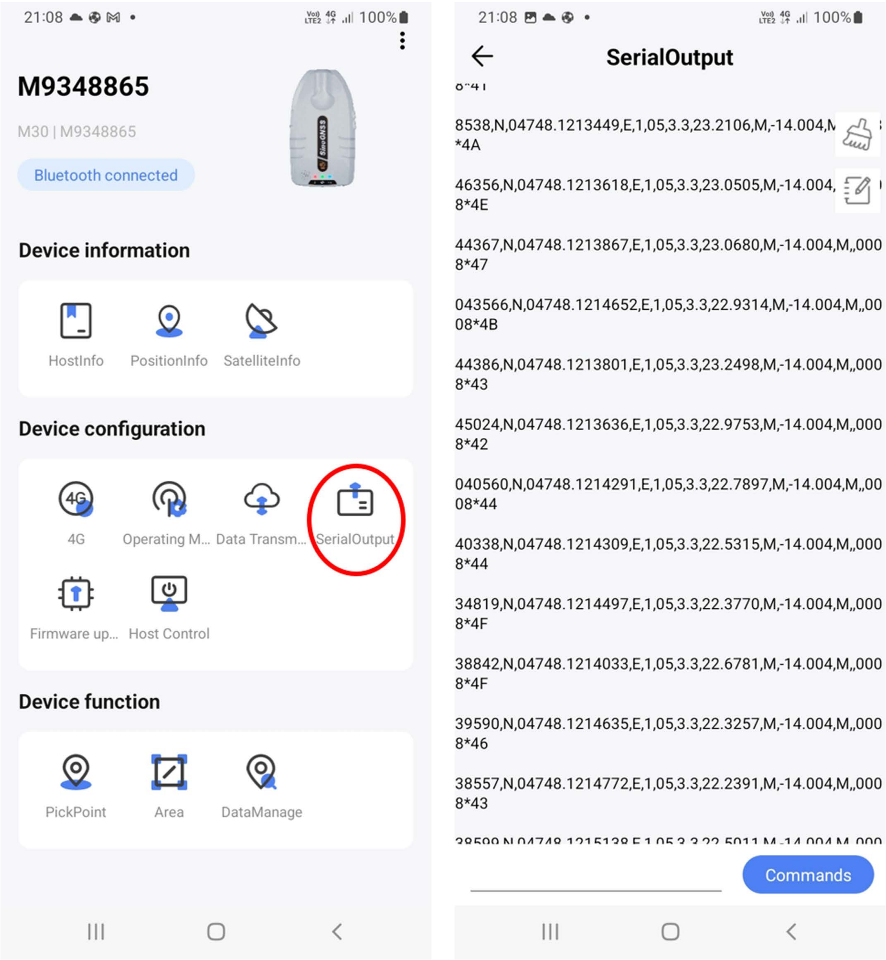
The Z30 receiver is equipped with a multi-frequency OEM board that allows it to access multiple satellite signals concurrently. This capability not only improves positioning accuracy but also ensures greater resilience against signal obstructions and multipath effects, which are common challenges in GNSS applications. By leveraging a broad spectrum of frequencies and satellite constellations, the Z30 can deliver precise and stable positioning data essential for various high-precision applications. One of the standout features of the Z30 is its user-friendly interface and connectivity options. The receiver integrates seamlessly with smartphones and other devices via Bluetooth, enabling easy configuration and data management. This integration is particularly beneficial for field operations where mobility and ease of use are critical. Additionally, the Z30 supports 4G connectivity, which facilitates real-time data transmission and remote monitoring through platforms like NaviCloud [14]. This capability is invaluable for applications that require constant data updates and remote access, such as real-time asset tracking and monitoring. The Z30 also features an intuitive LED indicator system on its front panel, which provides users with immediate visual feedback on the receiver's operational status, including power levels, satellite tracking, and data transmission status. The inclusion of both power and SOS buttons ensures that the device can be easily managed and operated even in emergency situations, enhancing its reliability in critical applications. Durability and ease of use are core aspects of the Z30's design. The receiver is built to withstand the rigors of fieldwork, featuring a robust housing that protects its high-precision electronics from environmental hazards such as moisture and vibration. Despite its rugged design, the Z30 maintains a compact and lightweight form factor, making it an ideal choice for applications that require both portability and durability [15]. The power supply flexibility of the Z30 is another significant advantage. It supports both internal batteries and external power banks, ensuring uninterrupted operation during extended field sessions. This versatility in power options allows users to adapt the device to various operational scenarios, reducing downtime and increasing efficiency. The SinoGNSS Z30 is not only a tool for high-precision GNSS applications but also a versatile device suitable for a wide range of uses. Its high-precision positioning capabilities make it ideal for geospatial applications such as land surveying, mapping, and construction. In these fields, the Z30 provides accurate and reliable data that is crucial for planning, monitoring, and executing projects. Furthermore, its ability to deliver real-time data makes it a valuable asset for dynamic applications like unmanned aerial vehicle (UAV) operations, where precise positioning is essential for navigation and data collection [16].

In summary, the SinoGNSS Z30 GNSS receiver is a sophisticated and reliable tool designed to meet the needs of high-precision GNSS applications. Its ability to track multiple satellite constellations and frequencies, coupled with its robust design and user-friendly features, makes it an indispensable device for professionals in fields such as surveying, construction, and UAV operations. The Z30's advanced capabilities and versatile design ensure that it can provide the accurate and reliable positioning data needed to support a wide range of technical and industrial applications.

2.2. Navigating Master Application

The Navigate Master software is an essential tool for managing the SinoGNSS Z30 receiver, offering a comprehensive suite of features tailored to optimize the receiver's functionality. This software is primarily used for the configuration and management of GNSS receivers via Bluetooth, ensuring efficient and precise data handling. One of the core functionalities is its ability to facilitate the initial setup and ongoing management of GNSS data transmission, which is crucial for applications requiring high-precision positioning. Upon establishing a Bluetooth connection between the Z30 receiver and a mobile device, users can configure various settings, including the activation of the mobile network and input of the Access Point Name (APN) to enable 4G connectivity. This connectivity is vital for real-time data transmission to cloud-based platforms such as NaviCloud or custom TCP/IP servers. The software allows users to input the specific address of the NaviCloud platform, ensuring that real-time positional data can be effectively managed and monitored remotely [17]. Moreover, the software supports the configuration of Ntrip Clients, enabling the Z30 receiver to receive correction services from local Continuously Operating Reference Stations (CORS) or a dedicated base station. This feature significantly enhances the accuracy of the positional data, achieving centimeter-level precision which is essential for applications in geospatial mapping, surveying, and UAV navigation.

The sofware also offers robust data management capabilities, including the ability to upload tracking data to the NaviCloud platform. This functionality is crucial for continuous monitoring and historical data analysis, providing users with the ability to track the receiver's movements and operational status over time. The software also supports electronic fence setups, which can trigger alerts when the receiver moves outside a predefined area, enhancing security and operational oversight. In addition, the SDK allows developers to use the ComNav command set through the SerialOutput feature which enables communication with the Z30 receiver. Figure 1 below shows the SerialOutput Feature:



```
8538,N,04748.1213449,E,1,05,3.3,23.2106,M,-14.004,
*4A

46356,N,04748.1213618,E,1,05,3.3,23.0505,M,-14.004,
8*4E

44367,N,04748.1213867,E,1,05,3.3,23.0680,M,-14.004,M,,000
8*47

043566,N,04748.1214652,E,1,05,3.3,22.9314,M,-14.004,M,,00
08*4B

44386,N,04748.1213801,E,1,05,3.3,23.2498,M,-14.004,M,,000
8*43

45024,N,04748.1213636,E,1,05,3.3,22.9753,M,-14.004,M,,000
8*42

040560,N,04748.1214291,E,1,05,3.3,22.7897,M,-14.004,M,,00
08*44

40338,N,04748.1214309,E,1,05,3.3,22.5315,M,-14.004,M,,000
8*44

34819,N,04748.1214497,E,1,05,3.3,22.3770,M,-14.004,M,,000
8*4F

38842,N,04748.1214033,E,1,05,3.3,22.6781,M,-14.004,M,,000
8*4F

39590,N,04748.1214635,E,1,05,3.3,22.3257,M,-14.004,M,,000
8*46

38557,N,04748.1214772,E,1,05,3.3,22.2391,M,-14.004,M,,000
8*43
```

Figure 1. SerialOutput in navigate master software.

The ComNav Command Set is a comprehensive collection of commands designed to control and configure ComNav OEM GNSS boards. These commands facilitate a wide range of functionalities, from basic configuration to advanced

GNSS data manipulation and control. The command set is meticulously structured to cater to various needs of GNSS applications, ensuring robust performance and flexibility.

The ComNav Command Set is categorized into several groups based on functionality [18]:

- System Configuration Commands: These commands are used to set up the basic parameters of the GNSS system. Commands like SAVECONFIG, LOADCONFIG, and FACTORYRESET allow users to save, load, and reset configurations, respectively, ensuring the GNSS board operates under the desired settings.
- Positioning and Navigation Commands: This category includes commands that control the positioning and navigation outputs. For instance, the LOG command enables logging of various GNSS data types, while the INTERFACEMODE command sets the communication interface parameters.
- GNSS Data Commands: Commands such as GPSEPHEM, BD2EPHEM, and GALFNAVRAWPAGE are used to retrieve satellite ephemeris data, which is crucial for precise positioning. These commands ensure that the GNSS receiver has the most up-to-date orbital information for satellites.
- Real-Time Kinematic (RTK) Commands: RTK is a high-precision GNSS technique, and the ComNav Command Set includes several commands to facilitate RTK operations. Commands like RTKSOURCE, RTKQUALITY, and RTKFIXHOLDTIME allow users to configure the RTK settings, ensuring accurate and reliable positioning.
- Satellite Configuration Commands: Commands such as SBASCONTROL and HEADING2 provide control over satellite-based augmentation systems (SBAS) and heading determination, enhancing the GNSS receiver's accuracy and reliability.
- Logging and Output Commands: The LOG command is pivotal for data logging, allowing users to specify which data types to log and at what intervals. The MARKPOS and MARKTIME commands are used to log precise event positions and times, critical for applications requiring timestamped location data.

The ComNav Command Set provided a powerful and flexible interface that was instrumental in this research, allowing precise control and configuration of the GNSS receiver used in the study. Utilizing its extensive range of commands, the GNSS system was tailored to meet the specific requirements of the UAV-based building localization mission. Specifically, satellite configuration commands were employed to isolate and engage individual GNSS constellations such as GPS, GLONASS, Galileo, SBAS, and BeiDou. This enabled a detailed comparative analysis of their positional accuracy. The flexibility ensured that the GNSS receiver was optimally configured for each satellite system, enhancing the reliability and precision of the collected data. The continuous updates and additions to the command set, reflecting ComNav's commitment to innovation and performance in GNSS technology, provided a robust framework for conducting high-precision geospatial measurements critical to the research objectives. The commands below were used in this research:

- The LOCKOUTSYSTEM command is a feature of the Z30 GNSS receiver that allows users to exclude entire satellite systems from being utilized in positional computations. This command can be particularly useful in scenarios where certain satellite systems may not be reliable or where interference might affect the accuracy of positioning data. For example, if a particular GNSS system, such as BeiDou, is experiencing issues or providing unreliable data, the LOCKOUTSYSTEM command can be used to prevent the receiver from using satellites from that system.
- The UNLOCKOUTSYSTEM command in the Z30 GNSS receiver's command set is used to reinstate a previously locked out GNSS system, allowing it to be included again in the solution computation. This command is essential when there is a need to re-enable the usage of a particular GNSS system that had been excluded due to issues such as interference or signal quality concerns. By executing the UNLOCKOUTSYSTEM command followed by the specific system name, users can quickly restore the functionality of the GNSS system without needing to reset the entire receiver configuration. For example, the command UNLOCKOUTSYSTEM BD2 would allow the BeiDou system to be reintegrated into the positional computations. This flexibility is crucial for ensuring that the GNSS receiver can adapt to changing conditions and optimize performance by leveraging the available satellite systems.

Navigate Master is a versatile and powerful tool that enhances the operational efficiency of the SinoGNSS Z30 receiver. Its comprehensive features for configuration, data transmission, and management make it indispensable for professionals requiring high-precision GNSS data for applications such as UAV navigation, geospatial mapping, and surveying. The integration of real-time data transmission and robust configuration options ensures that users can achieve optimal performance and reliability from their GNSS systems.

2.3. UAV-Based Building Localization Mission

A UAV-based building localization mission involves using unmanned aerial vehicles (UAVs) equipped with advanced positioning systems to determine the precise geographical location of buildings. This methodology leverages the precision of high-end GNSS receivers, combined with sophisticated software tools, to capture detailed spatial data crucial for urban planning, construction, disaster management, and geospatial mapping.

In this research, the UAV used was the DJI Mini 3 Pro, a compact yet powerful drone known for its high-resolution imaging and robust flight capabilities shown in **Figure 2** below.

The DJI Mini 3 Pro was managed using Dronelink software installed on an Android device. Dronelink is a versatile and advanced platform that provides precise location data and remote control capabilities for the UAV. It allows operators

Figure 2. DJI mini 3 pro.

to plan, execute, and monitor flights with high accuracy through its comprehensive suite of tools, which includes mission planning, automated flight controls, and real-time telemetry feedback [19]. The Dronelink software offers a highly customizable mission planning interface, enabling users to design complex flight paths that ensure comprehensive coverage of the target area. Features such as waypoint navigation, automated image capture, and dynamic flight adjustments enhance the efficiency and precision of the data collection process. Additionally, Dronelink's ability to integrate with various GNSS receivers ensures that the UAV operates with optimal navigational accuracy. The Android device running Dronelink was connected to a high-precision GNSS receiver, the SinoGNSS Z30, which supplied the accurate navigational information essential for the mission. This integration ensures that the positional data collected is of the highest accuracy, which is crucial for detailed geospatial mapping and building localization tasks. Using the DJI Mini 3 Pro in conjunction with Dronelink software and the SinoGNSS Z30 receiver, the mission was able to achieve precise localization of buildings. The high-resolution imagery captured by the UAV, combined with the accurate GNSS data, provided a robust dataset for creating detailed maps and models of the target area.

UAV-based building localization missions offer several advantages over traditional ground-based surveying methods. UAVs can cover large areas quickly and efficiently, significantly reducing the time and labor costs associated with manual surveys. The ability to capture high-resolution imagery and GNSS data in a single flight session enhances the overall efficiency of the localization process [20]. The aerial perspective provided by UAVs ensures comprehensive area coverage, allowing for the detection and mapping of features that may be difficult to observe from the ground. This capability is particularly beneficial in densely built urban environments where ground-based visibility is limited [21]. UAV-based localization is highly adaptable and can be deployed in various environments, including remote or hazardous areas where ground access is limited or unsafe. This flexibility makes UAVs an invaluable tool for a wide range of geospatial and engineering applications, from urban planning to environmental monitoring [22]. The use of high-precision GNSS receivers like the SinoGNSS Z30 ensures that the positional data collected is of the highest accuracy. This precision is crucial for applications that require detailed and reliable spatial information, such as construction management and disaster response planning [23]. Furthermore, UAV-based localization provides urban planners with detailed, accurate maps of building locations and other infrastructure. These maps are essential for making informed decisions about zoning, development, and resource allocation. The ability to quickly update maps as new buildings are constructed ensures that planners always have current information [24]. In construction, UAVs are used to monitor the progress of building projects. Accurate localization data allows project managers to verify that structures are being built according to plan and within specified tolerances. This can help identify potential issues early, reducing the risk of costly delays and rework.

After a natural disaster, UAVs can quickly survey affected areas to assess damage and locate buildings that may be unsafe. This information is vital for coordinating emergency response efforts and planning recovery operations. High-precision localization helps ensure that rescue teams can navigate efficiently and reach those in need as quickly as possible [25]. UAV-based building localization is also used to create detailed geospatial maps for various applications. These maps can be used for environmental monitoring, infrastructure management, and land use planning. The high resolution and accuracy of the data collected by UAVs make them an ideal tool for creating detailed, reliable maps [26].

UAV-based building localization missions leverage the advanced capabilities of UAVs and high-precision GNSS technology, such as the SinoGNSS Z30, to accurately determine the geographical location of buildings. The integration of Dronelink software for UAV control and precise GNSS data collection offers significant advantages in terms of efficiency, accuracy, and adaptability. These missions are essential for modern geospatial analysis and urban planning, providing reliable, high-precision data that can be used for a wide range of applications.

2.4. Kuwait Finder GIS Application

Kuwait Finder is a comprehensive GIS application developed by the Public Authority for Civil Information (PACI) in Kuwait, utilizing ESRI's advanced GIS technology. ESRI (Environmental Systems Research Institute), which is renowned for its sophisticated GIS software, which provides powerful tools for mapping, spatial analysis, and data integration. Kuwait Finder leverages ESRI's ArcGIS platform, which enhances its capabilities in terms of data accuracy, real-time updates, and user-friendly interfaces.

ESRI is a global leader in location services, powering its industry-leading mapping and spatial analytics products used by thousands of organizations worldwide. Recently, ESRI introduced the ArcGIS Platform, a location-focused platform-as-a-service (PaaS) offering that provides developers with direct access to ESRI's robust location services [27]. ArcGIS Platform enables developers to build powerful solutions with a comprehensive set of high-quality location services, allowing them to go to market faster using either ArcGIS APIs or open-source third-party APIs. It supports a cost-effective, developer-friendly business model where users can sign up for free and only pay for additional services used. This flexibility allows developers to create applications for web, mobile devices, desktops, and system-to-system integrations, usable both online and offline for indoor and outdoor purposes [28]. A detailed breakdown of ArcGIS Platform Services is listed below:

- Basemaps: ArcGIS Platform offers a global collection of ready-to-use, authoritative maps that can be integrated into applications with just a few lines of code [29]. These basemaps provide realistic depictions of the earth at multiple scales using authoritative data sources. The platform includes a vast library of pre-styled basemaps, ranging from neutral backgrounds to rich foreground maps emphasizing human geography, like streets, or physical geography, like topography. Users can even find basemaps with blended elevation data for enhanced decision-making. Additionally, a custom style-editor allows for the complete customization of basemaps, enabling users to select colors, patterns, and labels that meet their unique needs.
- Data Hosting: ArcGIS Platform allows users to host their data in the ArcGIS cloud, offering more than simple file hosting [30]. Users can create services based on their data that can be visualized, edited, and analyzed. Data hosting supports multiple file formats, including spreadsheets, shapefiles, and plain text files, and provides flexibility to access data as features, vectors, images, or GeoJSON. ESRI prioritizes data privacy, ensuring users retain ownership of their data without any telemetry information collection.
- Data Visualization: ArcGIS Platform provides advanced data visualization capabilities, allowing users to create unique, data-driven maps in 2D and 3D [31]. Users can incorporate thousands of features and visualizations based on multiple variables, style their maps with intelligent defaults tailored to their data, and use smart-mapping capabilities to eliminate guesswork in setting map properties. These features enable the creation of interactive, real-world 3D models of buildings, landscapes, and cities, enhancing the visual context and analytical depth of geospatial data.
- Geocoding and Search: The geocoding and search service in ArcGIS Platform enables users to search addresses and place names globally and display the results on a map [32]. The service supports single and batch address searches, providing textual descriptions such as nearest address, intersection, or place-name for map coordinates. Enhanced by an autosuggest feature, the service offers multiple address candidates as users type, ensuring quick and accurate location searches. ESRI's geocoding service is powered by authoritative reference data from commercial data providers, government agencies, and global partners, ensuring precise and reliable search results.
- Routing and Directions: The routing and directions service helps solve complex routing problems, widely used by major logistical companies to maximize efficiency and minimize costs. Users can find routes, generate turn-by-turn

directions, and perform intelligent network analysis, applying real-world constraints like traffic, U-turns, road barriers, and vehicle height limits. The service offers global coverage with localized directions, supports multi-vehicle routing, and helps optimize routes for cost-effective operations [33]. Additionally, users can perform network analysis to find optimal business locations, identify closest facilities, generate service areas, and create origin-destination cost matrices.

- Maps and Data: ArcGIS Platform provides access to an extensive library of maps and data, including demographic, statistical, and psychographic data [34]. The GeoEnrichment service allows users to analyze study areas and sites globally, adding context with data on people, places, and businesses. ArcGIS Living Atlas of the World offers curated maps and data layers, real-time live feeds on traffic, weather, and events, and high-resolution imagery from multiple providers. These resources enable users to visualize changes over time and conduct comprehensive geospatial analyses.
- Spatial Analytics: ArcGIS Platform offers a comprehensive set of tools for spatial analytics, revealing patterns and relationships in data [35]. These tools operate client-side for interactive experiences and server-side for scaling large data sets. The platform supports big data analytics, real-time analytics, advanced spatial tools, machine learning, and deep learning capabilities. By leveraging device resources and server-side analytics, users can build highly interactive applications and conduct in-depth spatial analyses.

ESRI's ArcGIS Platform empowers developers to create impactful geospatial applications with a comprehensive suite of location services, robust data hosting, and advanced spatial analytics. Its intuitive developer experience, cost-effective business model, and extensive geospatial resources make it an invaluable tool for building innovative solutions in the geospatial domain. One such application built on this powerful platform is Kuwait Finder, which offers detailed maps, address search capabilities, turn-by-turn navigation, and integrates various geospatial data layers, including satellite imagery, street maps, and land use information. The application provides high-resolution maps, real-time traffic updates, and information on public services, making it an essential tool for navigation and location-based services. ESRI's GIS technology allows Kuwait Finder to deliver high-precision geospatial data, supporting features such as dynamic mapping, spatial analytics, and comprehensive data visualization. **Figure 3** below shows screens from Kuwait Finder GIS application.

In the context of a UAV-based building localization mission, Kuwait Finder will be used to validate the accuracy of positional data obtained from the Sino-GNSS Z30 receiver mounted on a DJI Mini 3 Pro UAV. The application's detailed geographic information, powered by ESRI's ArcGIS, serves as a reliable reference for comparing the GNSS data collected by the UAV. This integration ensures that the positional data is accurate and reliable, critical for applications such as urban planning, construction, and disaster management. By cross-referencing

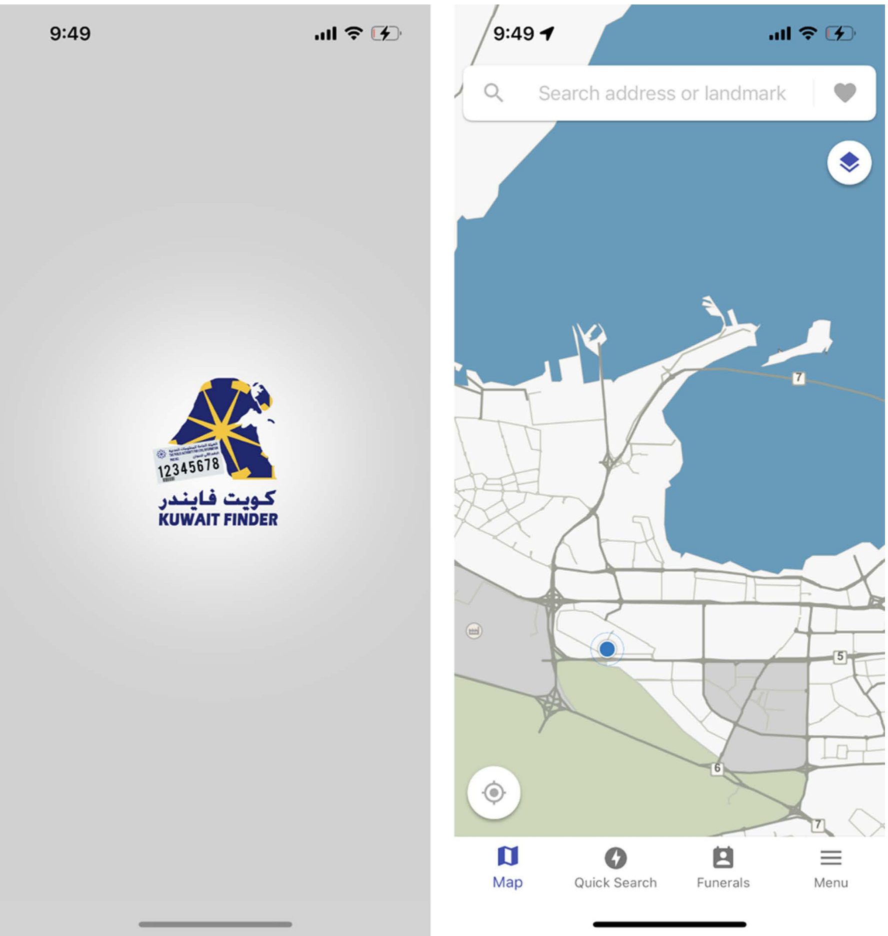


Figure 3. Kuwait finder application.

UAV-captured coordinates with Kuwait Finder's data, researchers can assess the precision of their GNSS data, enhancing the credibility of their geospatial analysis. The high accuracy, comprehensive coverage, and ease of use of Kuwait Finder, backed by ESRI's robust GIS technology, make it an invaluable tool for validating GNSS data and supporting a wide range of geospatial applications.

3. Results

3.1. Connecting to Single Satellites System

In this subsection, we detail the process of connecting the GNSS receiver to individual satellite systems and the subsequent data collection. The SinoGNSS Z30 GNSS receiver was employed to track signals from different GNSS constellations separately, including GPS, GLONASS, Galileo, SBAS, and BeiDou. This was achieved by configuring the receiver to connect to one satellite system at a time, enabling a detailed comparison of the positional accuracy provided by each constellation.

1) GPS-only Configuration

The first experiment involved connecting the GNSS receiver exclusively to the

GPS satellite system. The receiver was configured to track only GPS satellites, and data was collected for the latitude and longitude coordinates of the target building. This process was repeated multiple times to ensure the reliability and accuracy of the data. The following command allows the GPS system, which was previously locked out to be reinstated into the solution computation:

```
UNLOCKOUTSYSTEM GPS
```

2) GLONASS-only Configuration

Next, the receiver was configured to track only GLONASS satellites. Similar to the GPS configuration, multiple readings were taken to ensure data consistency. The GLONASS-only data provided an alternative set of coordinates, which were then compared to the GPS results to evaluate differences in positional accuracy. The following command enables the reactivation of GLONASS system that was previously excluded from the solution computation:

```
UNLOCKOUTSYSTEM GLONASS
```

3) Galileo-only Configuration

For the Galileo configuration, the receiver was set to track only Galileo satellites. Data was collected under the same conditions as the previous configurations, with multiple readings taken to ensure precision. The Galileo-only data was compared to both GPS and GLONASS results, contributing to a comprehensive analysis of the different satellite systems. The following command allows the Galileo system, previously excluded from the solution computation, to be reactivated:

```
UNLOCKOUTSYSTEM GALILEO
```

4) SBAS-only Configuration

The receiver was then configured to connect exclusively to SBAS satellites. SBAS provides augmentation services to enhance the accuracy and integrity of GNSS signals. The data collected under the SBAS-only configuration was compared to the previous systems to determine the effectiveness of SBAS in improving positional accuracy. The following command permits the reactivation of the SBAS system, which was previously excluded from the solution computation:

```
UNLOCKOUTSYSTEM SBAS
```

5) BeiDou-only Configuration

Finally, the receiver was set to track only BeiDou satellites. The data collection process was identical to the other configurations, with multiple readings taken to ensure accuracy. The BeiDou-only data was analyzed in conjunction with the other satellite systems to provide a comprehensive comparison of positional accuracy across different GNSS constellations. The following command reinstates the Galileo system, which had been previously excluded from the solution computation:

```
UNLOCKOUTSYSTEM BD3
```

3.2. Building Location Identification Using Kuwait Finder GIS Application

In this subsection, we present the results obtained from using drones equipped with the SinoGNSS Z30 GNSS receiver to identify the precise location of a building. The drone employed in this study was the DJI Mini 3 Pro, managed using the Dronelink software installed on an Android device. This setup allowed for high-precision data collection during multiple flights over the target building.

The primary objective was to capture accurate latitude and longitude coordinates of the building using various satellite systems configured individually. The results from these flights demonstrated the efficacy of the drone-GNSS integration in providing precise geospatial data. Table 2 below shows the latitude and longitude coordinates of the building, obtained using drones and various individually configured satellite systems.

Table 2. Latitude and Longitude coordinates of the Building Obtained using Drones*.

Satellite System	Longitude	Latitude	Number of Satellites
All Enabled	47.802023	29.298486	22
GPS-Only	47.802040	29.298478	11
GLONASS-Only	47.802009	29.298492	14
Galileo-Only	47.802036	29.298433	10
SBAS-Only	47.802062	29.298369	7
BeiDou-Only	47.802015	29.298482	12

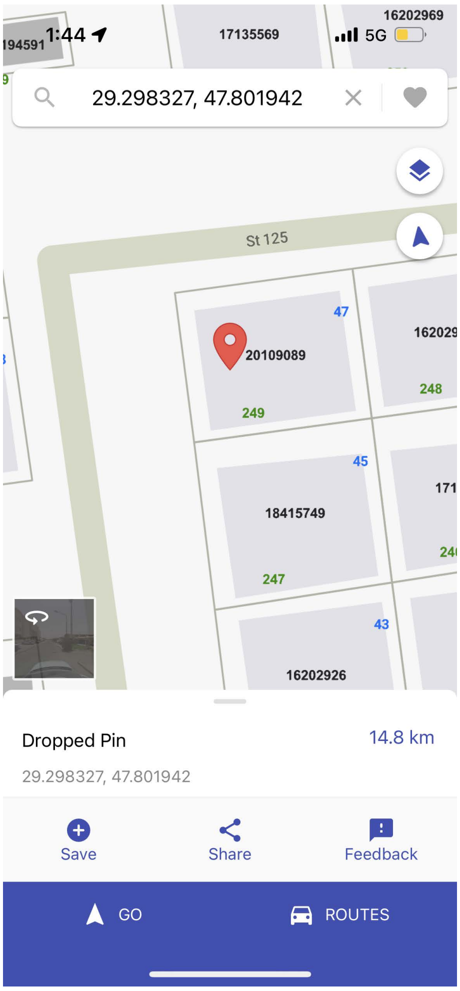
*To obtain robust and reliable data for each category under investigation, a series of experiments were conducted, with each Satellite being performed 10 times, and the average results were subsequently calculated and systematically compiled in a tabular format.

The data reveals significant variation in the number of satellites engaged by each system. When all satellite systems are enabled, the highest number of satellites, 22, is used, ensuring the most accurate location data. In contrast, when individual systems are used, the number of satellites decreases. GPS-Only utilizes 11 satellites, GLONASS-Only employs 14 satellites, Galileo-Only uses 10 satellites, SBAS-Only operates with 7 satellites, and BeiDou-Only engages 12 satellites. This variation highlights the differences in satellite availability and coverage among the different systems.

Appendix A includes detailed images from both DroneLink and Master Cloud software, illustrating the results discussed above. These images provide comprehensive visual documentation of the latitude and longitude coordinates, as well as the number of satellites engaged by each satellite system configuration.

3.3. Building Location Identification Using Kuwait Finder GIS Application

In this subsection, we utilize the Kuwait Finder GIS application to identify and verify the location of the building. The Kuwait Finder GIS application offers precise and reliable geospatial data, aiding in accurate building location identification. By leveraging this application, we can cross-reference the coordinates obtained from the various satellite systems and drone data to ensure consistency and accuracy. A screenshot from the Kuwait Finder GIS application is shown in **Figure 4** below, illustrating the exact location of the building, corroborating the previously discussed results.



29.298327, 47.801942

Dropped Pin 14.8 km

29.298327, 47.801942

Figure 4. Location using Kuwait finder application.

In geospatial terms, a datum is a reference point used for measuring locations on the Earth's surface [36]. In this study, the datum is defined as the precise geospatial reference point located at the center of the area of the plan view of the building. This central datum provides a consistent and accurate reference point for all measurements, ensuring that any positional deviations can be precisely assessed. From the above figure, it is shown that the location of the building is accurately pinpointed by a longitude of 29.298327 and a latitude of 47.801942.

4. Discussion

The accuracy of the results obtained from each single satellite system configuration was meticulously calculated and compared with the coordinates provided by the Kuwait Finder GIS application. This comparison aimed to determine the closeness of the GNSS-derived measurements to the true value, highlighting the precision and reliability of each satellite system in UAV-based building localization missions. The accuracy percentage is a statistical measure used to indicate how close a guess or prediction is to the actual value in percentage terms. It is essentially the complement of the percentage error, providing a positive metric for evaluating the correctness of a guess [37]. **Table 3** below shows the accuracy percentage of locations obtained from drone compared to the location obtained from Kuwait Finder GIS Application. Details of Accuracy percentage equation can be found in Appendix B.

Figure 5 below shows the scatter diagram presentation of the above results.

Table 3. Accuracy percentage of locations obtained from drone compared to the location obtained from Kuwait Finder GIS Application*.

Satellite System	Longitude	Latitude	Accuracy percentage of Longitude	Accuracy percentage of Latitude
All Enabled	47.802023	29.298486	0.000169449	0.000542693
GPS-Only	47.802040	29.298478	0.000205013	0.000515388
GLONASS-Only	47.802009	29.298492	0.000140162	0.000563172
Galileo-Only	47.802036	29.298433	0.000196645	0.000361795
SBAS-Only	47.802062	29.298369	0.000251036	0.000143353
BeiDou-Only	47.802015	29.298482	0.000152713	0.000529040

*To obtain robust and reliable data for each category under investigation, a series of experiments were conducted, with each Satellite being performed 10 times, and the average results were subsequently calculated and systematically compiled in a tabular format.

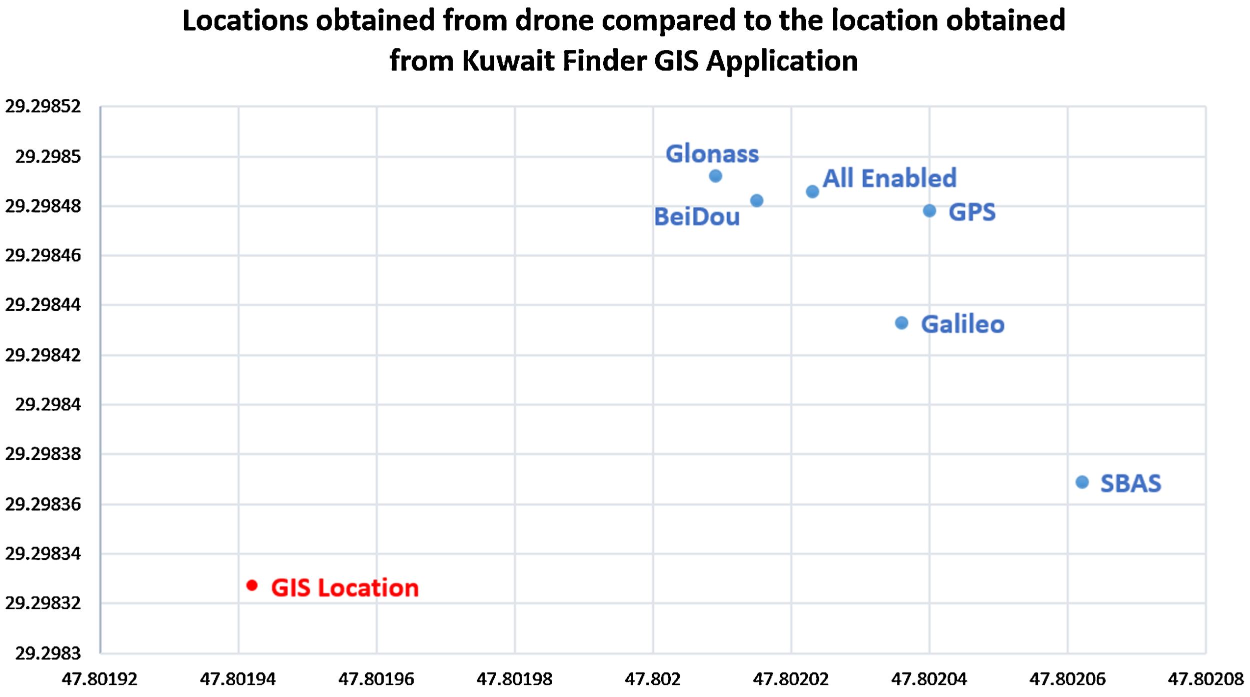


Figure 5. Kuwait finder application.

The results obtained from the UAV-based building localization mission indicate that the SBAS (Satellite-Based Augmentation System) configuration provided the highest accuracy, surpassing both Galileo and GPS. This outcome underscores the significant advantages of utilizing augmentation systems in geospatial applications. SBAS enhances the GNSS signals by providing correction data, which mitigates errors caused by atmospheric disturbances, satellite orbit inaccuracies, and other factors that typically degrade GNSS accuracy. The superior performance of SBAS in this study aligns with its designed purpose of improving the precision, integrity, and reliability of standard GNSS signals.

When configured to use only SBAS, the SinoGNSS Z30 receiver consistently produced positional data with minimal deviation from the true coordinates of the target building. The deviations were the smallest among all tested configurations, demonstrating SBAS's capability to deliver centimeter-level accuracy even in challenging environments where signal obstructions and multipath effects are prevalent. This level of precision is critical for applications requiring exact geospatial measurements, such as urban planning, precision agriculture, infrastructure monitoring, and disaster management.

In comparison, the Galileo-only configuration also exhibited high accuracy, but with slightly larger deviations than SBAS. Galileo, being a relatively newer GNSS constellation, has been designed with advanced technology and higher precision capabilities. The data collected using Galileo showed substantial reliability and minimal deviations, which are consistent with its known benefits, such as better signal quality and improved performance in urban environments. These characteristics make Galileo a strong contender for high-precision applications, though it still fell short of the augmented accuracy provided by SBAS in this study.

GPS, the most widely used GNSS system, also delivered reliable and precise positional data, albeit with slightly larger deviations compared to SBAS and Galileo. The GPS-only configuration demonstrated consistent accuracy, reinforcing its status as a robust and dependable system for various geospatial tasks. However, the data indicated that GPS's accuracy was not as enhanced as SBAS, highlighting the intrinsic limitations of using un-augmented GNSS signals in high-precision contexts. GPS's larger deviations can be attributed to its susceptibility to common GNSS errors, which SBAS effectively corrects.

The findings from this research underscore the critical importance of augmentation systems, such as SBAS, in enhancing the accuracy of GNSS data. SBAS's capability to provide real-time corrections significantly mitigates errors, thereby yielding more precise and reliable geospatial information. This heightened accuracy is particularly advantageous in fields that demand rigorous precision, such as surveying, construction, and UAV operations. The superior performance of SBAS in this study suggests that integrating augmentation systems with standard GNSS receivers is a highly effective strategy for achieving the highest levels of positional accuracy.

However, it is important to acknowledge that this study was conducted at a single building location, which may limit the generalizability of the results to other environments with varying signal conditions. The outcomes observed in this study might differ in areas characterized by different environmental factors, such as multipath effects, signal obstructions, or adverse atmospheric conditions. To address this limitation, future research should investigate the performance of SBAS and other GNSS configurations across a broader range of settings. Such studies would enhance the understanding of how these systems perform under diverse environmental conditions, thereby improving the generalizability and applicability of the findings.

Moreover, the results of this study suggest a hierarchical approach to selecting GNSS configurations based on the specific requirements of the application. While GPS and Galileo provide substantial accuracy for a wide array of tasks, SBAS should be prioritized in missions where precision is of paramount importance. The use of SBAS is particularly beneficial in challenging environments, where its corrective capabilities can significantly improve data quality.

The broader implications of these findings indicate that future geospatial technologies and applications should consider the integration of SBAS or similar augmentation systems to enhance accuracy. This study highlights the necessity of selecting the most appropriate GNSS configuration tailored to the specific demands of the task, ensuring optimal performance and reliability. By adopting this hierarchical approach to GNSS utilization, the geospatial field can achieve more efficient and precise practices, thereby advancing the discipline and its diverse applications.

5. Conclusions

This study aimed to evaluate the accuracy of different GNSS configurations in UAV-based building localization by comparing the positional data obtained from each satellite system with the known coordinates from the Kuwait Finder GIS application. Using the DJI Mini 3 Pro drone equipped with the SinoGNSS Z30 GNSS receiver, we conducted a series of flights to collect data under various configurations, including GPS-only, GLONASS-only, Galileo-only, SBAS-only, and BeiDou-only. The results demonstrated that the SBAS configuration provided the highest level of accuracy, with minimal deviation from the true coordinates of the building. This superior performance highlights the effectiveness of SBAS in enhancing GNSS accuracy through real-time corrections, making it an ideal choice for applications requiring the highest precision, such as urban planning, precision agriculture, and disaster management. Galileo and GPS configurations also exhibited high accuracy, though slightly less precise than SBAS. Galileo's advanced technology and design contributed to its reliable performance, while GPS's widespread use and robustness were reaffirmed through consistent data accuracy. GLONASS and BeiDou configurations provided reliable data as well, though with slightly larger deviations, indicating their suitability as complementary systems in multi-GNSS solutions. The comparative analysis of these GNSS configurations underscores the critical role of selecting the appropriate system based on specific application requirements. While GPS and Galileo offer useful accuracy for a wide range of tasks, SBAS should be prioritized for missions where precision is paramount. The integration of high-precision GNSS data with reliable reference standards, such as Kuwait Finder, ensures robust and valid geospatial analyses, supporting diverse applications in urban planning, construction monitoring, and beyond. Future research should focus on optimizing multi-GNSS solutions, exploring the potential of emerging technologies like real-time kinematic (RTK) positioning and precise point positioning (PPP), and investigating the impact of environmental factors on GNSS accuracy. Advanced algorithms and machine learning techniques could further enhance the precision and reliability of geospatial measurements.

In conclusion, the study validates the effectiveness of using drones equipped with advanced GNSS technology for high-precision building localization. The findings highlight the strengths of SBAS, GPS, Galileo, and BeiDou, offering a comprehensive understanding of the current state of GNSS technology and its applications in geospatial science. The integration of augmentation systems like SBAS with traditional GNSS receivers provides a robust framework for achieving the highest levels of positional accuracy, ensuring reliable and accurate geospatial data collection across various professional fields.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Colomina, I. and Molina, P. (2014) Unmanned Aerial Systems for Photogrammetry and Remote Sensing: A Review. *ISPRS Journal of Photogrammetry and Remote Sensing*, **92**, 79-97. https://doi.org/10.1016/j.isprsjprs.2014.02.013

[2] Eisenbeiss, H. (2009) UAV Photogrammetry. DISS. ETH NO. 18515, Institute of Geodesy and Photogrammetry, ETH Zurich.

[3] Hugenholtz, C.H., Whitehead, K., Brown, O.W., Barchyn, T.E., Moorman, B.J., LeClair, A., *et al.* (2013) Geomorphological Mapping with a Small Unmanned Aircraft System (sUAS): Feature Detection and Accuracy Assessment of a Photogrammetrically-Derived Digital Terrain Model. *Geomorphology*, **194**, 16-24. https://doi.org/10.1016/j.geomorph.2013.03.023

[4] Anderson, K. and Gaston, K.J. (2013) Lightweight Unmanned Aerial Vehicles Will Revolutionize Spatial Ecology. *Frontiers in Ecology and the Environment*, **11**, 138-146. https://doi.org/10.1890/120150

[5] Rakha, T. and Gorodetsky, A. (2018) Review of Unmanned Aerial System (UAS) Applications in the Built Environment: Towards Automated Building Inspection Procedures Using Drones. *Automation in Construction*, **93**, 252-264. https://doi.org/10.1016/j.autcon.2018.05.002

[6] Stuart, A. and Friedland, C.J. (2011) A Survey of Unmanned Aerial Vehicle (UAV) Usage for Imagery Collection in Disaster Research and Management. 9*th International Workshop on Remote Sensing for Disaster Response*, **8**, 1-8.

[7] Watts, A.C., Ambrosia, V.G. and Hinkley, E.A. (2012) Unmanned Aircraft Systems in Remote Sensing and Scientific Research: Classification and Considerations of Use.

Remote Sensing, **4**, 1671-1692. https://doi.org/10.3390/rs4061671

[8] Westoby, M.J., Brasington, J., Glasser, N.F., Hambrey, M.J. and Reynolds, J.M. (2012) 'Structure-from-Motion' Photogrammetry: A Low-Cost, Effective Tool for Geoscience Applications. *Geomorphology*, **179**, 300-314. https://doi.org/10.1016/j.geomorph.2012.08.021

[9] Zhang, C. and Kovacs, J.M. (2012) The Application of Small Unmanned Aerial Systems for Precision Agriculture: A Review. *Precision Agriculture*, **13**, 693-712. https://doi.org/10.1007/s11119-012-9274-5

[10] Li, T., Zhang, B., Xiao, W., Cheng, X., Li, Z. and Zhao, J. (2020) UAV-Based Photogrammetry and LiDAR for the Characterization of Ice Morphology Evolution. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, **13**, 4188-4199. https://doi.org/10.1109/jstars.2020.3010069

[11] Tahar, K.N. and Ahmad, A. (2012) A Simulation Study on the Capabilities of Rotor Wing Unmanned Aerial Vehicle in Aerial Terrain Mapping. *International Journal of the Physical Sciences*, **7**, 1300-1306. https://doi.org/10.5897/ijps11.969

[12] Nex, F. and Remondino, F. (2013) UAV for 3D Mapping Applications: A Review. *Applied Geomatics*, **6**, 1-15. https://doi.org/10.1007/s12518-013-0120-x

[13] ComNav Technology Ltd. (2023) SinoGNSS® Z30 User Guide. Version 1.0. https://www.comnavtech.com/

[14] Attaran, M., Attaran, S. and Celik, B.G. (2017) Promises and Challenges of Cloud Computing in Higher Education: A Practical Guide for Implementation. *Journal of Higher Education Theory and Practice*, **17**, 20-38.

[15] ComNav Technology Ltd. (2023) SinoGNSS Z30 Portable GNSS Receiver. https://www.comnavtech.com/

[16] Urban, R., Štroner, M. and Kuric, I. (2020) The Use of Onboard UAV GNSS Navigation Data for Area and Volume Calculation. *Acta Montanistica Slovaca*, **25**, 361-374. https://doi.org/10.46544/AMS.v25i3.9

[17] ComNav Technology Ltd. (2023) SinoGNSS Z30/M10/M10 Mini User Guide. Version 1.0. http://www.comnavtech.com.

[18] ComNav Technology Ltd. (2022) ComNav OEM Board Reference Manual. Revision 2.3. http://www.comnavtech.com.

[19] Boente, A., Eustaquio, T., da Fonseca, V.P., de Oliveira, T.E.A. and Rosa, P.F.F. (2021) Small Scale Unmanned Aircraft System and Photogrammetry Applied for 3D Modeling of Historical Buildings. *The Twelfth International Conference on Sensor Device Technologies and Applications SENSORDEVICES* 2021, Athens, 14-18 November 2021, 14-18.

[20] Bemis, S.P., Micklethwaite, S., Turner, D., James, M.R., Akciz, S., Thiele, S.T., *et al.* (2014) Ground-Based and UAV-Based Photogrammetry: A Multi-Scale, High-Resolution Mapping Tool for Structural Geology and Paleoseismology. *Journal of Structural Geology*, **69**, 163-178. https://doi.org/10.1016/j.jsg.2014.10.007

[21] Ouyang, J., De Bei, R., Fuentes, S. and Collins, C. (2020) UAV and Ground-Based Imagery Analysis Detects Canopy Structure Changes after Canopy Management Applications. *OENO One*, **54**, 1093-1103. https://doi.org/10.20870/oeno-one.2020.54.4.3647

[22] Li, Y., Qiao, G., Popov, S., Cui, X., Florinsky, I.V., Yuan, X., *et al.* (2023) Unmanned Aerial Vehicle Remote Sensing for Antarctic Research: A Review of Progress, Current Applications, and Future Use Cases. *IEEE Geoscience and Remote Sensing Magazine*, **11**, 73-93. https://doi.org/10.1109/mgrs.2022.3227056

[23] Chen, X., Hopkins, B., Wang, H., O'Neill, L., Afghah, F., Razi, A., *et al.* (2022) Wildland Fire Detection and Monitoring Using a Drone-Collected RGB/IR Image Dataset. *IEEE Access*, **10**, 121301-121317. https://doi.org/10.1109/access.2022.3222805

[24] Martinez, J.G., Gheisari, M. and Alarcón, L.F. (2020) UAV Integration in Current Construction Safety Planning and Monitoring Processes: Case Study of a High-Rise Building Construction Project in Chile. *Journal of Management in Engineering*, **36**, No. 3. https://doi.org/10.1061/(asce)me.1943-5479.0000761

[25] Gomez, C. and Purdie, H. (2016) UAV-Based Photogrammetry and Geocomputing for Hazards and Disaster Risk Monitoring—A Review. *Geoenvironmental Disasters*, **3**, Article No. 23. https://doi.org/10.1186/s40677-016-0060-y

[26] Koeva, M., Muneza, M., Gevaert, C., Gerke, M. and Nex, F. (2016) Using UAVs for Map Creation and Updating. A Case Study in Rwanda. *Survey Review*, **50**, 312-325. https://doi.org/10.1080/00396265.2016.1268756

[27] Nowak, M.M., Dzióbek, K., Ludwisiak, Ł. and Chmiel, J. (2020) Mobile GIS Applications for Environmental Field Surveys: A State of the Art. *Global Ecology and Conservation*, **23**, e01089. https://doi.org/10.1016/j.gecco.2020.e01089

[28] Maurya, S.P., Ohri, A. and Mishra, S. (2015) Open Source GIS: A Review. *Proceedings of National Conference on Open Source GIS: Opportunities and Challenges*, Varanasi, 9-10 October 2015, 150-155.

[29] Dangermond, J. (2012) Creating Our Future. *Proceedings of the Third GeoDesign Summit Conference*, Redlands, 5-6. https://www.esri.com/~/media/files/pdfs/news/arcnews/fall2014/fall-2014.pdf

[30] Kholoshyn, I., Bondarenko, O., Hanchuk, O. and Shmeltser, E. (2019) Cloud ArcGIS Online as an Innovative Tool for Developing Geoinformation Competence with Future Geography Teachers. arXiv: 1909.04388. https://doi.org/10.48550/arXiv.1909.04388

[31] Fleming, J., Marvel, S.W., Supak, S., Motsinger-Reif, A.A. and Reif, D.M. (2022) ToxPi*GIS Toolkit: Creating, Viewing, and Sharing Integrative Visualizations for Geospatial Data Using ArcGIS. *Journal of Exposure Science & Environmental Epidemiology*, **32**, 900-907. https://doi.org/10.1038/s41370-022-00433-w

[32] Shah, T.I., Bell, S. and Wilson, K. (2014) Geocoding for Public Health Research: Empirical Comparison of Two Geocoding Services Applied to Canadian Cities. *Canadian Geographies/Géographies Canadiennes*, **58**, 400-417. https://doi.org/10.1111/cag.12091

[33] Albalawneh, D.A. and Afendee Mohamed, M. (2022) Evaluation of Using Genetic Algorithm and ArcGIS for Determining the Optimal-Time Path in the Optimization of Vehicle Routing Applications. *Mathematical Problems in Engineering*, **2022**, Article 7769951. https://doi.org/10.1155/2022/7769951

[34] Donnelly, F.P. (2010) Evaluating Open Source GIS for Libraries. *Library Hi Tech*, **28**, 131-151. https://doi.org/10.1108/07378831011026742

[35] Gao, J. (2021) Fundamentals of Spatial Analysis and Modelling. CRC Press. https://doi.org/10.1201/9781003220527

[36] Turconi, L., Nigrelli, G. and Conte, R. (2014) Historical Datum as a Basis for a New GIS Application to Support Civil Protection Services in NW Italy. *Computers & Geosciences*, **66**, 13-19. https://doi.org/10.1016/j.cageo.2013.12.008

[37] Brownstone, D. (1996) Using Percentage Accuracy to Measure Neural Network Predictions in Stock Market Movements. *Neurocomputing*, **10**, 237-250. https://doi.org/10.1016/0925-2312(95)00052-6

Appendix A

The details of locations obtained from drones capturing the building location for each satellites system can be found in **Figure A1** below:

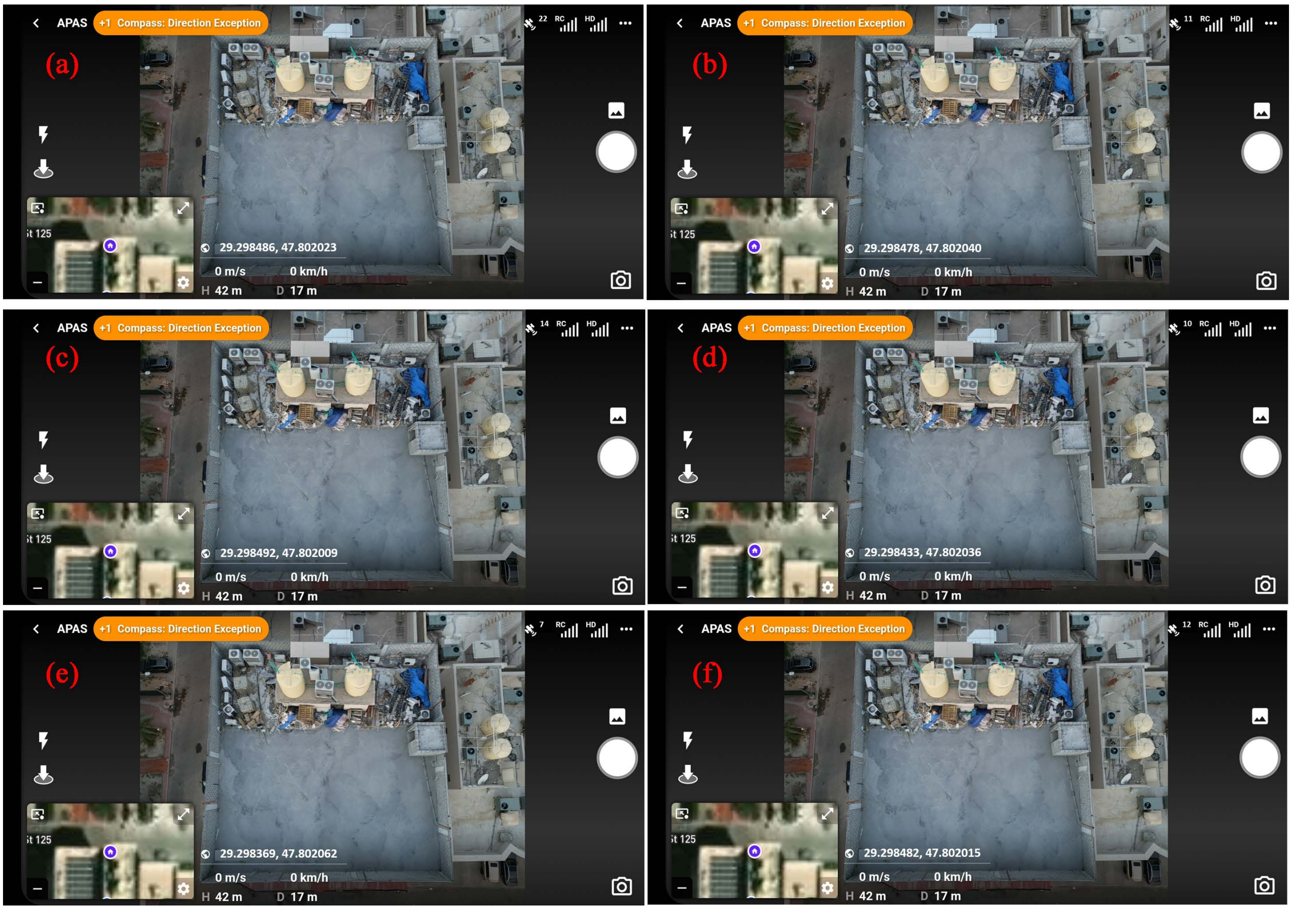


Figure A1. Capturing Location Building using Drones for Single Satellites System. (a) All Enabled, (b) GPS-Only, (c) Gloanass-Only, (d) Galiloe-Only, (e) SBAS-Only, (f) BeiDou-Only.

Appendix B

Percentage Accuracy: A percentage accuracy is a measure of how close a measurement or test is to the true or theoretical value of that measurement or test. This is a ratio of the difference between true and measured divided by the true value.

The Percentage Accuracy formula:

$$A = 100 - [(Tv - Ov)/Tv * 100]$$

where:

A: The percentage Accuracy.

Tv: is the true or theoretical value.

Ov: is the observed or measured value.