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Vertical Accuracy Studies for Unmanned Aerial Vehicles (UAVs)

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Abstract

The increasing use of Unmanned Aerial Vehicles (UAVs) in mapping and surveying has necessitated a comprehensive understanding of their vertical accuracy performance. The use of UAVs in mapping projects has rapidly expanded due to their efficiency, cost-effectiveness, and high spatial resolution. Vertical accuracy, a critical criterion for UAV-derived Digital Elevation Models (DEMs) and orthophotos, influences their use in applications such as cadastral map production, environmental monitoring and infrastructure inspection, and digital elevation model production. Factors affecting vertical accuracy include sensor resolution, ground control point (GCP) distribution, and flight altitude. This study provides valuable information for professional UAV practitioners seeking to optimize vertical accuracy in photogrammetric projects and photogrammetric workflows. This article examines recent developments in vertical accuracy studies in UAV photogrammetry worldwide, analyzing the factors affecting accuracy, survey methodologies, and comparative performance in different geographic regions. A comprehensive table combining vertical Root Mean Square Error (RMSE) values from multiple studies highlights trends and challenges. Recommendations for optimizing vertical accuracy in UAV mapping are also provided.

1. Introduction

Close Range Photogrammetry (CRP), traditionally conducted using ground-based cameras mounted on tripods or handheld devices, has long been established as a reliable and versatile technique for generating precise three-dimensional (3D) models, detailed topographic maps, and accurate measurements of terrain, buildings, and various physical objects. This method involves capturing overlapping images from multiple viewpoints and applying photogrammetric processing to reconstruct spatial geometry. Its flexibility and relatively low cost have made CRP widely applicable across numerous fields, ranging from archaeological documentation and architectural conservation to industrial inspection and small-scale engineering projects [1-7].

The scope of close-range photogrammetry extends from the precise measurement of small objects—such as artifacts, machine parts, or biological specimens—to medium-scale applications like surveying buildings, infrastructure components, and landscape features. The high level of detail achievable through close-range methods makes it invaluable for scenarios demanding fine spatial resolution and geometric accuracy.

Despite its benefits, close-range photogrammetry is inherently limited by several practical and environmental factors. One of the primary constraints is the requirement for direct line-of-sight between the camera and the subject, which restricts its effectiveness in complex or obstructed environments. Surveying areas with steep slopes, dense vegetation, or large-scale terrains often presents significant challenges, as these conditions impede camera placement and obstruct clear views necessary for accurate image capture. Additionally, extensive fieldwork is typically required to position cameras at multiple vantage points, which can be time-consuming, labor-intensive, and sometimes unsafe or impractical, especially in inaccessible or hazardous locations. [7-11].

To overcome these limitations, aerial photogrammetric methods—particularly those utilizing Unmanned Aerial Vehicles (UAVs)—offer significant advantages. UAV-based photogrammetry extends the capabilities of traditional close-range techniques by providing access to otherwise unreachable or dangerous areas and enabling rapid data acquisition over large spatial extents. The elevated vantage points of UAVs facilitate comprehensive coverage, reduce ground-based logistical constraints, and improve overall data quality by minimizing occlusions caused by terrain and vegetation. Consequently, photogrammetric methods, when combined with UAV technology, address many of the disadvantages associated with terrestrial close-range measurements, enhancing efficiency and expanding application possibilities in fields such as environmental monitoring, forestry, agriculture, and urban planning [38,39,40].

An Unmanned Aerial Vehicle (UAV) is an unmanned aircraft system designed to operate without a human onboard. UAVs can be remotely controlled by an operator using ground-based controls or flown autonomously on pre-programmed flight plans using onboard navigation systems[12-15].. UAVs are a core component of Unmanned Aircraft Systems (UAVs), which include not only the aircraft itself but also the ground control station, data transmission infrastructure, software interfaces, and a payload, often consisting of sensors or cameras for specific applications[16-20].

UAVs represent a fusion of aeronautical engineering, robotics, navigation technology, and remote sensing. They typically include inertial measurement units (IMUs), GNSS (Global Navigation Satellite System) receivers (often with RTK or PPK capabilities for high precision), barometric sensors, and automatic flight controllers. These components enable the UAV to maintain stable flight, navigate accurately in three-dimensional space, and collect spatial or spectral data with high precision.

UAVs come in a variety of configurations—fixed-wing, rotary-wing (multi-rotor), and VTOL—each with different performance characteristics suited to different operational requirements. Fixed-wing UAVs offer longer flight endurances and broader coverage, while multi-rotor UAVs offer vertical takeoff and landing (VTOL) capabilities, making them ideal for narrow environments

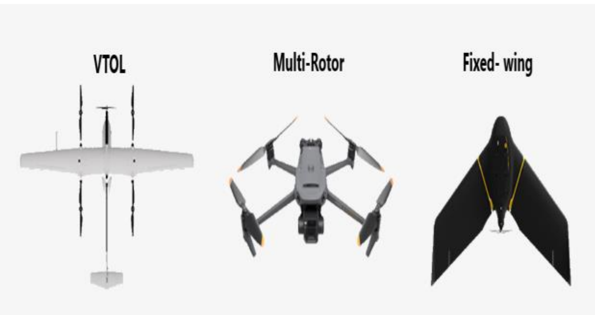

Figure 1. Unmanned Aerial Vehicles (UAVs) types

Fixed-wing Unmanned Aerial Vehicles (UAVs) are aerial platforms that generate lift using fixed wings. Fixed-wing unmanned aerial vehicles (UAVs) typically take off from runways, catapults, or manual launch mechanisms to take off.

Figure 2. Unmanned Aerial Vehicles (UAVs) Take off styles

Rotary-wing UAVs, including four–rotor (quadcopters), six-rotor (Hexacopter) UAVs, and eight-rotor UAVs (octocopters), generate lift through one or more rotors. These UAVs can hover vertically, hover, take off, and land.

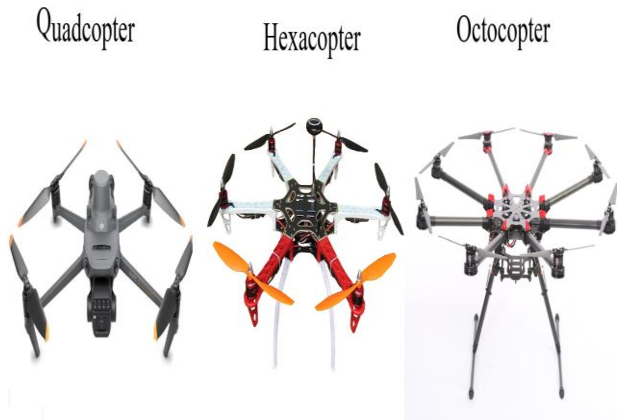

Figure 3. Quadcopter, Hexacopter, Octocopter

VTOL (Vertical Takeoff and Landing) fixed-wing UAVs combine the aerodynamic efficiency of fixed-wing aircraft with the vertical mobility of rotary-wing systems. These hybrid platforms use vertical lift mechanisms (rotors or tilt wings) for takeoff and landing and switch to fixed-wing flight for horizontal navigation.

Figure 4. VTOL UAV

Table 1. VTOL Fixed-Wing vs. Rotary-Wing UAVs

Parameter	Rotary-Wing UAVs (e.g., Multirotor)	Fixed-Wing UAVs	VTOL Fixed-Wing UAVs
Flight Mechanism	Lift generated by spinning rotors	Aerodynamic lift from wings	Combines both: rotors for VTOL, wings for cruise
Takeoff & Landing	Vertical take-off and landing	Requires runway or launcher	Vertical take-off and landing
Flight Time (Endurance)	Short (15–40 minutes typical)	Long (60–180+ minutes)	Moderate to long (45–120+ minutes)
Flight Speed	Low (10–30 km/h)	High (60–120 km/h)	Moderate to high (50–100 km/h)
Coverage Area per Flight	Small (0.5–2 km²)	Large (5–20+ km²)	Large (5–20 km²)
Mapping Efficiency	Low (slow, high overlap needed)	High (large area in short time)	High
Payload Capacity	Low to medium (0.2–2 kg)	Medium to high (1–5+ kg)	Medium to high (1–4+ kg)
Spatial Resolution (GSD)	Very high (due to low altitude)	High (depends on flight altitude)	High (can cruise low if needed)
Wind Resistance	Low to moderate (5–10 m/s optimal)	High (15–20 m/s tolerable)	Moderate to high (10–15 m/s)
Suitability for Small Area Surveys	Excellent	Poor	Good
Suitability for Large Area Mapping	Poor	Excellent	Excellent
Common Use Cases	Urban mapping, construction, inspection, archaeology	Corridor mapping, agriculture, topography	Precision agriculture, cadastral surveys, corridor mapping in remote areas

Unmanned Aerial Vehicles (UAVs), also known as drones, have transformed the field of photogrammetry and remote sensing by providing high-resolution spatial data quickly and flexibly. Orthophoto maps generated from UAV imagery have gained traction in various fields, including agriculture, forestry, urban planning, and archaeology [21, 22, 23]. Their ability to produce both planimetric and altimetric information makes them indispensable for Digital Elevation Model (DEM) generation and terrain analysis.

Despite advancements, vertical accuracy remains a significant concern in UAV-based mapping, as elevation errors can compromise subsequent analyses like flood modeling, slope stability assessment, and construction monitoring [24, 25]. While horizontal accuracy is often sufficient for many applications, vertical precision is more challenging due to factors like sensor noise, flight parameters, and terrain complexity [26].

This review consolidates findings from over 20 global UAV studies, including Murat Yakar's extensive research on UAV orthophoto mapping in Turkey [1], and expands the scope to include diverse environments such as mountainous regions, agricultural plains, and urban centers [22, 27, 28]. The paper omits case studies but provides a comparative analysis of vertical accuracy metrics, aiming to guide researchers and practitioners in optimizing UAV survey designs for improved altimetric results

2. Definitions of vertical accuracy

Vertical accuracy refers to the degree of closeness between a measured elevation value obtained through surveying or remote sensing methods and its corresponding true or reference elevation, typically derived from highly accurate ground surveys or established benchmarks. It is a critical metric in geospatial science, topographic mapping, and photogrammetric surveying, serving as a key indicator of the quality and reliability of elevation data products. This metric becomes especially important when evaluating the performance of Unmanned Aerial Vehicle (UAV) systems used to generate Digital Elevation Models (DEMs), Digital Surface Models (DSMs), and orthophotos, which are foundational datasets in numerous environmental, engineering, and planning applications.

Accurate vertical measurements are essential because errors in elevation data can propagate through subsequent processing and analyses, leading to significant inaccuracies in terrain representation. Such inaccuracies may manifest as distorted or unrealistic surface models that misrepresent natural or built environments. For example, elevation errors can result in erroneous calculations of earthwork volumes in construction projects, leading to budget overruns or misinformed decision-making. In hydrological modeling, inaccurate terrain data can distort watershed boundaries, affecting flood risk assessments and water resource management.

Moreover, vertical inaccuracies can cause spatial misalignments when integrating UAV-derived data with other geospatial datasets from different sources, such as satellite imagery, LiDAR scans, or cadastral maps [43].These misalignments compromise the overall coherence of multi-source data fusion efforts and reduce the utility of integrated models for analysis and visualization. Therefore, rigorous assessment, quantification, and transparent reporting of vertical error metrics—such as Root Mean Square Error [RMSE), Mean Absolute Error (MAE), or bias—are essential practices for ensuring the reliability, comparability, and repeatability of UAV-derived geospatial products.

Understanding and communicating vertical accuracy not only improves confidence in UAV survey results but also informs appropriate applications and limitations of the data, guiding users in making well-informed decisions. Consequently, vertical accuracy remains a cornerstone consideration in the design, execution, and validation of UAV surveying missions across diverse disciplines, including agriculture, forestry, urban planning, disaster management, and environmental monitoring.Vertical Accuracy refers to the closeness of an elevation measurement to the true vertical position of a point. It is commonly assessed using Root Mean Square Error (RMSE) against reference ground control points or benchmarks.

$$RMSE_z = \sqrt{\frac{1}{n}\sum_{i\_1}^{n}(\text{Zmeasured}_i - \text{Zreference}_i)^2} \quad (1)$$

Where Zmeasured_i is the elevation derived from the UAV survey, and Zreference_i is the known elevation.

3. Affecting Factors of Vertical Accuracy in UAV Photogrammetry

Vertical accuracy in UAV photogrammetric products is influenced by a complex interplay of hardware, flight parameters, processing workflows, and environmental conditions.

3.1. Sensor and UAV Platform

The choice of sensor plays a crucial role in determining the quality and reliability of data collected by UAV platforms. Multirotor UAVs, such as those from the DJI Phantom series, are often equipped with high-resolution RGB cameras that capture detailed imagery suitable for a wide range of applications including photogrammetry, inspection, and environmental monitoring. These multirotor systems offer significant operational flexibility due to their ability to take off and land vertically, hover, and maneuver precisely in confined or complex environments. However, a major limitation of multirotor UAVs is their relatively short flight endurance and limited coverage area per flight, often constrained by battery life. This makes them more suitable for small to medium-sized survey areas where high spatial resolution and maneuverability are prioritized [22, 29].

In contrast, fixed-wing UAVs are designed for longer endurance and greater coverage areas, enabling efficient surveying of large terrains. When equipped with advanced positioning systems such as Real-Time Kinematic (RTK) or Post-Processed Kinematic (PPK) GNSS receivers, fixed-wing UAVs can achieve superior vertical accuracy in their geospatial data products. The combination of stable, smooth flight paths and precise georeferencing through RTK/PPK correction significantly reduces positional errors, making fixed-wing platforms highly effective for applications demanding accurate elevation models and topographic mapping over expansive regions [28, 30]. This makes them ideal for large-scale agricultural monitoring, forestry management, and infrastructure inspection projects where accuracy and area coverage are critical.

Moreover, recent advancements in sensor fusion techniques have demonstrated that integrating data from multiple sensors onboard UAVs can greatly enhance the overall quality and accuracy of spatial information, particularly in challenging environments. For instance, combining UAV-based photogrammetry with Light Detection and Ranging (LiDAR) or multispectral imaging leverages the complementary strengths of these sensors. Photogrammetry provides high-resolution color imagery, while LiDAR contributes precise three-dimensional structural data that is less affected by lighting conditions and vegetation cover[44,45]. Multispectral sensors add valuable spectral information that can improve vegetation analysis and material differentiation. Such sensor fusion approaches have been shown to improve vertical accuracy and provide richer datasets, especially in areas with dense vegetation, uneven terrain, or complex urban infrastructure, where single-sensor methods may struggle to deliver accurate results [29, 30,31]

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3.2. Flight Planning Parameters

Flight altitude, image overlap, camera angle, and flight path geometry are critical parameters that directly influence the vertical accuracy and overall quality of UAV photogrammetric outputs [26]. The selection and optimization of these parameters are essential to achieve high-fidelity three-dimensional (3D) reconstructions and accurate Digital Elevation Models (DEMs).

Numerous studies recommend maintaining flight altitudes between 50 and 120 meters as an optimal range that balances ground sample distance (GSD) and survey area coverage [22, 25]. Flying too low can result in excessively high-resolution images but limits the area covered per flight, increasing operational time and data volume. Conversely, flying too high reduces image resolution and may compromise the ability to detect fine surface details necessary for precise elevation modeling. Thus, choosing a flight height within this range allows for efficient data acquisition while maintaining sufficient image detail for accurate photogrammetric processing.

Image overlap—both forward (along the flight direction) and side (between adjacent flight lines)—is equally important to ensure adequate redundancy and enable reliable feature matching during 3D reconstruction. Typical forward and side overlap percentages range from 75% to 85%, which provides multiple viewpoints of each ground point, minimizing data gaps and enhancing the robustness of tie points used in photogrammetric algorithms [25, 32]. Insufficient overlap increases the risk of incomplete or inaccurate reconstructions, while excessive overlap may lead to unnecessary data redundancy and longer processing times.

In addition to nadir (straight-down) imagery, incorporating oblique camera angles—where the camera is tilted relative to the vertical axis—significantly improves terrain coverage and reduces occlusions caused by terrain relief, vegetation, or man-made structures [29]. Oblique images capture side perspectives that reveal features hidden from vertical views, thereby enriching the 3D point cloud density and completeness. This approach is particularly valuable in areas with complex topography or built environments.

Furthermore, flight path geometry plays a crucial role in data quality. Designing flight plans that include cross-flight lines—flight lines flown perpendicular or diagonal to the main survey direction—creates additional overlapping perspectives and improves the distribution of tie points across the survey area. This redundancy enhances the stability and accuracy of the photogrammetric model, reduces geometric distortions, and leads to more consistent vertical accuracy throughout the dataset.

In summary, careful optimization of flight altitude, image overlap, camera angles, and flight path geometry is essential to maximizing vertical accuracy in UAV surveys. These parameters work synergistically to provide comprehensive and high-quality datasets that support reliable 3D surface reconstruction and precise elevation modeling.

3.3. Ground Control Points (GCPs) and Georeferencing

The number, spatial distribution, and accuracy of Ground Control Points (GCPs) are fundamental factors in minimizing vertical errors in UAV-based surveys. GCPs act as precisely surveyed reference points on the ground, providing essential benchmarks that enable accurate georeferencing and calibration of UAV-derived data products such as digital elevation models (DEMs) and orthophotos. Ensuring an adequate number of GCPs that are well-distributed throughout the survey area is critical for reducing systematic and random vertical errors. Poorly placed or insufficient GCPs can lead to spatial biases and distortions in the resulting elevation data, compromising the overall survey accuracy.

While advancements in UAV technology have introduced Real-Time Kinematic (RTK) and Post-Processed Kinematic (PPK) Global Navigation Satellite System (GNSS) receivers that can be integrated onboard UAV platforms, these systems significantly reduce the dependence on ground-based control points by providing centimeter-level positioning accuracy in real time or during post-processing [21, 23, 28]. RTK/PPK systems enable UAVs to achieve highly precise geolocation data, which enhances vertical accuracy and accelerates data acquisition workflows by minimizing the need for extensive GCP surveys. Despite this, it remains best practice to include a set of well-distributed GCPs in any UAV survey. These GCPs serve as a quality control measure to validate and assess the positional accuracy of the UAV data, helping to detect any discrepancies or calibration errors that may occur during data capture or processing.

Moreover, careful consideration of GCP placement across areas with varying elevation is vital to prevent vertical bias in the final datasets [33]. In terrains with significant topographic relief, clustering GCPs in a limited elevation range can cause distortions or tilting effects in the generated elevation models. Strategically distributing GCPs across the full range of terrain elevations ensures that vertical corrections are accurately applied throughout the survey area, thereby improving the consistency and reliability of the elevation data. This approach is particularly important in mountainous or hilly regions, where elevation gradients can be steep and complex.

In summary, while onboard RTK/PPK GNSS technology has enhanced UAV survey efficiency and positional accuracy, the thoughtful deployment of an adequate number of well-distributed and accurately surveyed GCPs remains essential for ensuring the highest quality vertical accuracy and for validating the integrity of UAV-derived geospatial products.

3.4. Environmental and Terrain Factors

Vegetation cover, building density, and terrain ruggedness are among the primary environmental factors that introduce noise and occlusions during UAV data acquisition, significantly degrading vertical accuracy [22, 26]. Dense vegetation, such as forest canopies or thick crop fields, often obstructs the line of sight between the UAV sensors and the ground surface, making it difficult to capture accurate ground points. Similarly, in urban areas with high building density, the complexity of structures causes shadowing and occlusions, which can result in incomplete or distorted data capture. Rugged terrain further complicates data acquisition by creating abrupt elevation changes and shadowed areas, challenging the photogrammetric matching algorithms and increasing the likelihood of errors in elevation modeling.

To overcome these challenges in complex landscapes, the deployment of a dense network of Ground Control Points (GCPs) becomes essential. GCPs serve as precisely surveyed reference points on the ground that improve the georeferencing accuracy of UAV data. By increasing the number and spatial distribution of GCPs, surveyors can better constrain the photogrammetric model, reducing vertical Root Mean Square Error (RMSE) and improving overall accuracy [29, 34]. However, placing and surveying a large number of GCPs can be labor-intensive and costly, especially in difficult-to-access or hazardous areas.

In addition to increasing GCP density, integrating multiple sensor modalities through sensor fusion techniques has proven effective in enhancing vertical accuracy under challenging conditions. For example, combining UAV photogrammetry with LiDAR or multispectral sensors leverages the unique strengths of each system—LiDAR's ability to penetrate vegetation and capture precise 3D structure complements the high-resolution imagery from photogrammetry, improving ground surface modeling and reducing RMSE in vegetated or urban environments.

Atmospheric conditions, such as humidity, temperature fluctuations, and varying air density, can also influence the performance and calibration of UAV sensors, as well as the quality of GPS signals used for positioning [27]. High humidity and temperature variations may cause sensor drift or calibration shifts, leading to subtle measurement errors during data collection. Furthermore, adverse atmospheric conditions can degrade GPS signal strength and accuracy, particularly in areas with limited satellite visibility or multipath effects caused by nearby buildings or terrain features. These factors collectively contribute to vertical accuracy degradation and must be considered when planning UAV surveys, sensor calibration, and data processing workflows.

4. Comparative Analysis of Vertical Accuracy in UAV Studies

Vertical accuracy stands as a fundamental measure of the quality and reliability of UAV-based surveys, especially when the primary objectives involve generating accurate elevation models and orthophotos. In geospatial and remote sensing disciplines, the precision of vertical measurements plays a crucial role in ensuring that derived products authentically represent the physical characteristics of the surveyed area.

Elevation modeling, including Digital Elevation Models (DEMs) and Digital Surface Models (DSMs), is highly dependent on accurate vertical data to portray the true shape and structure of the terrain and surface features. DEMs provide a bare-earth representation by excluding vegetation and man-made objects, while DSMs include all surface elements, such as buildings and vegetation canopy. The fidelity of these models is vital for a wide range of applications, including flood risk assessment, land use planning, infrastructure design, forestry management, and environmental monitoring. Any errors in vertical measurements can distort these models, leading to inaccurate representations of slope, elevation gradients, and volumetric calculations, which can have serious implications in engineering and scientific analyses.

Similarly, orthophotos—geometrically corrected aerial images that preserve a uniform scale across the image—require a high level of vertical accuracy to minimize spatial distortions caused by variations in terrain elevation. These distortions, if not properly corrected, can lead to misalignments and inaccuracies in spatial measurements, undermining the utility of orthophotos for precise mapping, cadastral surveys, and geographic information system (GIS) applications. High vertical accuracy ensures that orthophotos can be reliably used for tasks such as feature extraction, change detection, and detailed spatial analysis, where positional accuracy is paramount.

Moreover, the vertical accuracy of UAV-derived products influences the integration of datasets from multiple sources, such as satellite imagery, terrestrial laser scanning, and traditional surveying. Consistent and accurate vertical referencing is essential for seamless data fusion, enabling comprehensive spatial analyses and decision-making processes that depend on multi-source geospatial information.

In summary, vertical accuracy is a cornerstone of UAV photogrammetric surveys, underpinning the reliability and precision of elevation models and orthophotos. Achieving and maintaining high vertical accuracy enhances the credibility of UAV data products and expands their applicability across diverse scientific, engineering, and operational domains.

This section synthesizes findings from an extensive body of global UAV research that has systematically evaluated vertical accuracy across various platforms, sensors, and environmental conditions. A commonly employed metric in these studies is the vertical Root Mean Square Error (RMSE), which quantifies the average magnitude of vertical deviations between UAV-derived elevation data and ground-truth measurements. RMSE provides an objective and standardized means to assess the precision of elevation data by summarizing the squared differences and offering an interpretable error value, typically expressed in meters or centimeters.

Across these studies, reported vertical RMSE values vary depending on factors such as sensor type, UAV platform, flight parameters, ground control strategies, and post-processing techniques. These variations highlight the importance of carefully selecting UAV configurations and operational protocols to meet specific accuracy requirements. For instance, surveys employing UAVs equipped with RTK/PPK GNSS systems generally report lower vertical RMSE values, reflecting the enhanced positional accuracy afforded by real-time or post-processed correction methods. Conversely, UAV surveys relying solely on standard GPS may exhibit higher vertical errors due to less precise positioning.

Additionally, environmental conditions such as terrain complexity, vegetation density, and lighting can influence vertical accuracy outcomes. Challenging environments tend to increase vertical RMSE values due to difficulties in feature matching and ground point extraction during photogrammetric processing. To address such challenges, some studies have explored sensor fusion approaches—integrating photogrammetric data with LiDAR or multispectral sensors—to improve vertical accuracy and reduce RMSE.

By compiling and comparing vertical RMSE results from diverse global UAV applications, this section provides critical insights into the current state of vertical accuracy in UAV surveys, identifies best practices, and underscores the factors that practitioners should consider to optimize the quality of elevation models and orthophotos generated from UAV data.

Table 1 below summarizes vertical accuracy metrics from diverse UAV applications, UAV platforms, and geographic settings. The reported vertical RMSE values vary considerably, reflecting differences in hardware configurations, survey methods, terrain types, and environmental factors.

Table 2. Vertical RMSE from UAV Studies

Study	UAV System / Sensor	Vertical Accuracy (RMSE, m)	Remarks
Yakar et al., 2023(21)	Multi-rotor UAV + RTK + GCPs	0.020 – 0.045	RTK + GCP optimized accuracy
Pathak et al., 2024(22)	DJI Phantom 4 RTK	0.061	Mountainous terrain, flight height ~80 m
Çallı et al., 2023(23)	UAV with RTK & Non-RTK GNSS	0.020 – 0.040	RTK significantly improves vertical accuracy
Elaksher et al., 2023(24)	Multi-rotor UAV + RTK + GCP	0.025 – 0.040	Comparative study of UAV configurations
Aktan et al., 2022(25)	SenseFly eBeeX	0.035 – 0.045	Village-scale orthophoto mapping
Refai et al., 2024(26)	Multi-rotor UAV + varied GCPs	0.030 – 0.060	Overlap and GCP pattern influence
Liu et al., 2018(27)	Multi-rotor UAV	0.032	High precision true digital orthophoto
Istanbul Technical University, 2025(28)	Fixed-wing UAV + RTK/PPK	0.006	High precision for large area correction
Gao et al., 2022(29)	UAV LiDAR	0.015 – 0.030	Sensor fusion approach
Yuan, 2025(30)	DJI Phantom 4 RTK	0.020 – 0.040	Agricultural land monitoring
Stamenković et al., 2024(31)	DJI P4 Multispectral	0.025	Multispectral UAV mapping
Tamimi & Toth, 2024(32)	DJI Matrice 350 RTK	0.018	Urban mapping application
Maboudi & Ghaffarian, 2022(33)	Multi-rotor UAV	0.025 – 0.050	Impact of path planning on accuracy
Zhuangqun et al., 2024(34)	DJI Phantom 4 RTK	0.022 – 0.040	Precision agriculture
Susilo et al., 2023(35)	Multi-rotor UAV	0.030 – 0.050	Road damage detection
Bayanlou & KhoshboreshMasouleh, 2020(36)	VTOL fixed-wing UAV	0.04	Orthophoto mosaic over 26.3 ha

The collected data show that the best vertical accuracy (sub-centimeter RMSE) is attainable in well-planned UAV surveys utilizing RTK/PPK technology, efficient GCP distribution, and stable flight platforms [28]. In contrast, surveys in complex terrains or with fewer GCPs tend to have higher vertical errors [22, 26].

The variability among studies underscores the importance of tailored flight planning and processing workflows based on the specific mapping objectives and terrain characteristics [5, 13]. This comparison also highlights the increasing role of sensor fusion and advanced UAV designs in pushing the limits of vertical accuracy [29, 36]. Photogrammetry is used in every field, from measuring small objects to wide-area mapping with drones [37,38,39,40]

5. Recommendations for Optimizing Vertical Accuracy in UAV Surveys

Based on a comprehensive review of relevant literature and empirical studies, the following best practices are highly recommended for maximizing vertical accuracy in UAV photogrammetric mapping projects:

1. Use RTK/PPK-capable UAV platforms whenever possible: UAV systems equipped with Real-Time Kinematics (RTK) or Post-Processed Kinematics (PPK) Global Navigation Satellite System (GNSS) technology provide highly accurate real-time or post-processed positioning data, significantly reducing the need for extensive Ground Control Point (GCP) networks. This advancement increases absolute vertical accuracy, simplifies fieldwork, and improves overall survey efficiency, particularly in large or inaccessible areas where GCP deployment is challenging [21, 28].

2. Deploy a well-distributed GCP network, especially in terrain with variable elevation: The spatial distribution and density of GCPs plays a critical role in minimizing vertical deviations and correcting systematic errors during photogrammetric processing. Strategically placing GCPs at different elevation levels (especially in areas with significant topographic variations) helps limit vertical errors and improves the accuracy and consistency of elevation models. Correct GCP placement also provides valuable checkpoints for quality control and validation of UAV data [23, 33].

3. Optimize flight parameters for consistent 3D reconstruction quality: Choosing appropriate flight altitudes and image overlap ratios is crucial to ensure sufficient image resolution and coverage for robust photogrammetric processing. Recommended flight altitudes typically range from 50 to 120 meters and provide a balance between ground sampling distance (GSD) and coverage. Maintaining image overlap ratios above 75%, including both front and side overlaps, improves feature matching and point cloud density, leading to more accurate and detailed 3D models [22, 25,41].

4. Use sensor fusion techniques in complex or vegetated terrain: Combining UAV photogrammetry with complementary sensor methods, such as LiDAR and multispectral imaging, can significantly improve vertical accuracy, especially in environments where dense vegetation or complex surface features obscure direct ground visibility. LiDAR's ability to penetrate vegetation and capture precise three-dimensional structure, combined with spectral information from multispectral sensors, enriches elevation models and improves classification accuracy [29, 31].

5. Carefully plan survey geometry to reduce occlusions and improve data quality: Incorporating oblique imagery and cross-flight lines into the survey design helps mitigate the effects of occlusions caused by terrain features, buildings, or vegetation. Oblique imagery captures side views of objects and terrain that rare (vertical) imagery cannot capture, resulting in higher point cloud density and improved model integrity. Cross-flight lines add redundant coverage from multiple angles, improving anchor matching and reducing spatial errors [26, 32,42].

6. Consider environmental factors during survey planning: External conditions such as atmospheric humidity, temperature fluctuations, and dense vegetation can affect sensor performance and GPS signal quality. Planning UAV surveys during favorable weather conditions and considering seasonal or diurnal variation in vegetation can help minimize these sources of error. Furthermore, understanding local atmospheric influences allows for better calibration and correction during data processing [22, 27].

By adhering to these best practices, UAV surveyors and geospatial experts can significantly improve the vertical accuracy of their photogrammetric output and provide more reliable and precise elevation data suitable for a wide range of scientific, engineering, and operational applications.

6. Conclusion

Vertical accuracy is a fundamental element of UAV photogrammetric mapping, directly impacting the usability and reliability of orthophotos and Digital Elevation Models (DEMs) across a wide range of applications. High vertical accuracy is essential to ensure that these spatial products accurately represent the true surface elevations and features of the measured terrain, which in turn impacts decision-making in areas such as environmental monitoring, urban planning, agriculture, construction, and disaster management. This article presents a comprehensive review of existing literature and studies reporting vertical root mean square error (RMSE) values. This review aims to clarify the typical vertical accuracy ranges achieved by various UAV systems, identify the key factors affecting vertical accuracy, and recommend best practices for UAV photogrammetric measurements.

The findings from this comprehensive review indicate that under controlled conditions, vertical RMSE can be as low as a few millimeters, particularly when using UAVs equipped with Real-Time Kinematics (RTK) or Post-Processed Kinematics (PPK) GNSS systems. However, under practical and more variable field conditions, typical vertical RMSE values range from approximately 0.02 meters to 0.06 meters. These variations are highly dependent on many factors, including the type and quality of the UAV platform, sensor characteristics, flight parameters, terrain complexity, ground control strategies, and environmental conditions during data collection.

Furthermore, new technologies and methodological advancements continue to push the boundaries of achievable vertical accuracy. Innovations such as sensor fusion, which integrates photogrammetric data with LiDAR, multispectral, or thermal sensors, improve vertical accuracy by combining complementary data sources that overcome the limitations inherent to each sensor. Advanced UAV designs, including hybrid vertical takeoff and fixed-wing platforms, improve flight stability and endurance, and enable higher-quality data collection over larger areas with better georeferencing capabilities.

Looking ahead, future research should prioritize the development of standardized frameworks for accuracy assessment to ensure consistent and comparable reporting of vertical errors across studies and applications. Furthermore, more seamlessly integrating multi-sensor data streams and automating error detection and correction through machine learning and AI hold significant potential to further enhance the reliability and efficiency of UAV-based vertical mapping. These advances will be critical in expanding the operational scope of UAV surveys and ensuring their output meets the increasingly stringent accuracy requirements of modern geospatial applications.

Author contributions

Hacı Murat Yılmaz: Conceptualization, Formal Analysis, Editing, **Murat Yakar**: Data curation, Methodology, Supervision

Conflicts of interest

The authors declare no conflicts of interest.

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