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ACCURACY ASSESSMENT OF THAILAND'S NETWORK REAL TIME KINEMATIC (NRTK) FOR UNMANNED AERIAL VEHICLE (UAV) PHOTOGRAMMETRY

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ABSTRACT: Unmanned aerial vehicle (UAV) photogrammetry is a technology used to create highly accurate maps, and the real-time kinematic (RTK) global navigation satellite system (GNSS) network has been implemented by several organizations to support their missions. Recent advancements in computer vision have driven progress in photogrammetry, alongside the development of more accessible UAVs equipped with GNSS technology. This paper evaluates the accuracy of UAV imagery and processing using ground control points (GCPs) with coordinates from the Thailand RTK GNSS network. The study area is located on the Sathing-Phra Peninsula in Songkhla Province, southern Thailand, covering approximately 174 hectares with a total of 660 images. The average ground sampling distance (GSD) was around 4.35 cm. The processed photogrammetry system used 8 GCPs via the GNSS RTK network, and results were compared with 25 checkpoints from a static survey. The UAV photogrammetry results showed a horizontal accuracy for orthomosaics and vertical accuracy for the digital surface model (DSM), with CE 95 values of 6.99 cm and 12.44 cm, respectively, as per the NSSDA standard. These results comply with the Thailand UAV Surveying for Engineering (TUSE) standards. According to the 2014 American Society for Photogrammetry and Remote Sensing (ASPRS) standards, horizontal accuracy class I and vertical accuracy class II should be applied. The map scale factor (MSF) standard was 1:160, with a contour interval of 20 cm. Additionally, the orthomosaic DSM can be imported into open-source programs for use in a web GIS online system, enabling local agencies to retrieve and utilize the data.

Keywords: Unmanned aerial vehicle, Network RTK, Digital surface model, Orthoimagery

1. INTRODUCTION

Currently, UAVs and GNSSs (Global Navigation Satellite Systems) are quickly becoming the go-to means for gathering on-demand aerial imagery across industries such as construction, surveying, insurance, and mining. The implementation of innovative UAV solutions has been triggered by a larger number of potential users. UAVs are at the crossroads of many disciplines, such as photogrammetry, computer vision, and several applied remote sensing applications [1]. The interaction between these fields currently presents the greatest challenge for developing innovative, fit-for-purpose, and efficient solutions. The GNSS is widely utilized in most systems that require an absolute position. This is because of its accuracy, availability, and reliability [2]. Thus, providing high-accuracy receivers will eventually increase the number of GNSS-related applications. This technology is widely used in various fields, such as disaster monitoring, autonomous driving, and the Internet of Things [3]. A GNSS model was also used to estimate sea surface heights to bridge the gap between tide gauges and altimetric measurements in the coastal zones [4]. Two methods are predominantly used to provide real-time centimetre-level GNSS positioning services: traditional network RTK (NRTK) technology and precise point positioning RTK (PPP-RTK) technology [5]. Various groups have widely used GNSSs to support the data processing models included in urban studies. The accuracy of the measurement and data processing methods in studies in urban areas is very important, and the use of RTK GNSS is one solution to increase the accuracy of the data. In urban areas, signal problems become obstacles to determining positions and in navigation [6]. In Turkey, between Nurdağı and Gaziantep, 22 test points over a 52 km line were based on five stations from the continuously operating reference stations (CORS) network. The findings revealed planimetric accuracies better than 5 cm, and height accuracies better than 10 cm via NRTK techniques [7]. These results meet the accuracy requirements for classical GPS techniques in topographic map production, making the NRTK techniques more economical and sufficiently accurate than the long-term static GPS observations. Thailand is establishing a national positioning infrastructure by integrating data from the CORSs of various government agencies nationwide. The National CORS Data Center (NCDC) can provide unified high-accuracy coordinates to government agencies, the private sector, and the general public; it supplies RTK GNSS network services with centimetre-level accuracy nationwide [8]. The RTK network in Thailand installed and serviced the Department of Lands, Department of Structure and City & Country Planning, Hydro Informatics Institute (Public Organization), and Royal Thai Survey Department in 2022, which has 250 GNSS CORS stations [9]. The data obtained from the RTK GNSS network are highly accurate and spatially precise; the horizontal coordinates and form datum include the atmosphere information. It can be used for a wide range of purposes, including surveying, and can be combined with various survey technologies, such as construction surveys, hydrographic surveys, and the services span from aerial surveys to UAV surveys [10], all for mapping and producing spatial data.

Private UAVs are currently the hobbyist's product most frequently used for aerial photography, but there is high potential for their use in mapping. UAVs are now receiving increased attention for consumer applications since the prices are very affordable. The costs are drastically reduced because of the low-cost navigation and control devices as well as imaging sensors. UAVs are receiving increased attention for consumer applications since their prices are affordable, and they are equipped with a GNSS and initial measurement unit (IMU), which adds the essential requirements for automatic aerial surveys [11]. UAV-generated images and photogrammetry techniques are used to process high-spatial-resolution ortho imagery, digital surface models (DSMs), and digital elevation models (DEMs) [12]. The ability of a professional-grade UAV such as the DJI Phantom 4 RTK to achieve such high precision in photogrammetry highlights its advanced capabilities. The chosen location at Wuhan University, with its diverse terrain, provided a comprehensive test environment to showcase these capabilities. The horizontal accuracy is 1–3 cm, and the vertical accuracy is 4–6 cm [13]. The absence of GNSS signals under bridges and in tunnels makes it difficult to achieve precise georeferencing. Ground control points (GCPs) are often used to mitigate this issue, but their placement can be challenging in such environments [14]. Employing GCPs is essential to providing a centimetre-accuracy photogrammetric output. Using GCPs in mapping is vital because the outputs obtained from photogrammetry come with the actual measurements of the model [15].

In the past, we utilized GNSS static methods to determine the coordinates of the GCPs. This traditional approach, while accurate, requires extensive time and complex postprocessing to ensure precision. Currently, we have shifted to using the RTK GNSS network for this process, which provides real-time data collection, greatly improving efficiency. We expect this method to meet the mapping standards.

2. RESEARCH SIGNIFICANCE

This study is highly relevant for advancing the integration of UAV photogrammetry and RTK GNSS technology in high-accuracy mapping. By demonstrating the effectiveness of using GCPs with RTK GNSS networks to produce precise spatial data, this research highlights the potential to streamline mapping processes while maintaining adherence to established accuracy standards, such as ASPRS 2014. The novel application of Thailand's RTK GNSS network in this context is particularly impactful, as it showcases the scalability and reliability of this approach for various engineering projects. The findings provide valuable insights into current practices, promoting more efficient and cost-effective mapping solutions.

3. THAILAND’S RTK GNSS NETWORK

The GNSS technology of CORS with Network RTK (NRTK) provides data consisting of carrier phase and code range measurements in support of three-dimensional positions that have improved availability. Highly accurate positioning can be achieved by using data from multiple GNSSs, such as GPS (USA), GLONASS (Russia), Galileo (EU), BeiDou (China), QZSS (Japan), IRNSS, and NavIC (India), resulting in the introduction of GNSS technology [16], which can result in more variety. This approach can also be used for the prevention and mitigation of harmful substances, positioning services for surveying, mapping, and urban planning; and it can even be applied to engineering design machine control and survey high-precision agricultural work intelligent facilities. Thailand has developed a GNSS RTK network infrastructure and data appliance for management. This might enhance the country's competitiveness and prepare it for a business revolution and an expansion of Thai industries. Surveyors, GIS users, engineers, scientists, and thus the general public who collect GNSS data, can use RTK network data to increase the precision of their positions. The CORS-enhanced postprocessed coordinates approach centimetre-levels relative to the national spatial arrangement, both horizontally and vertically. NRTK uses GNSS data in conjunction with ground-based continuously operating networks to improve real time positioning to an accuracy of several centimetres [17]. NRTK provides reference station redundancy within the system; for example, if observations from one reference station are unavailable, a solution is possible since the observations are gathered and processed during a joint network adjustment. Currently, several solution methods are also applied in NRTK; there are existing solutions within the market, including the Virtual Reference Station (VRS), individualized Master–Auxiliary corrections (iMAX), and Area–Parameter corrections (FKP) methods [18].

In Thailand, the VRS technique is currently the most popular and efficient method of transmitting corrections through a data link to network users for RTK positioning. The basic theory of the VRS method is to transform measurements made at the actual reference stations to the location of the VRS, and therefore, to a different location at the same epoch. The CORS station network in Thailand began to develop and establish a network system in 1996 through the Department of Public Works and Town & Country Planning (DPT), which was used in surveys for mapping and town planning [19]. The Royal Thai Survey Department (RTSD) set up a CORS station where the data are processed later for surveying. In 2008, the Department of Lands (DOL) created a CORS station network (Fig. 1) with the Thai GNSS and Space Weather Information Data Center, which manages a comprehensive GNSS and sensor database.

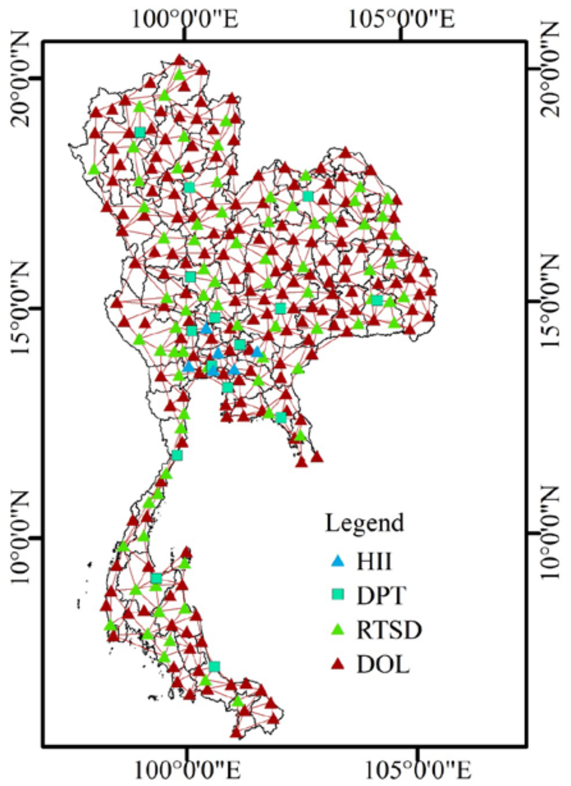

Fig. 1 The Thailand GNSS RTK Network

The centre operates and maintains various stations, data servers, and backup systems. The data collected and maintained are crucial for several fields, including GNSS positioning, and accurate GNSS data are vital for precise positioning applications. This network is the first network that can provide a kinetic survey conducted immediately on the basis of the VRS principle for cadastre surveys and other survey applications, including UAV photogrammetry.

4. METHODOLOGY

4.1 Study Area and Objective

To ensure high horizontal and vertical accuracy for the project's ortho-imagery and digital surface model (DSM), it is essential to consider the specific characteristics of the study area and the available technology. Given that the location is a peninsula on the seashore, factors such as the GNSS RTK network coverage and the unique coastal terrain play significant roles. The study area details the location of the Jathing-Phra subdistrict, Sathing-Phra peninsula, Songkhla Province in southern Thailand. With coordinates of approximately 7.45 degrees latitude and 100.42 degrees longitude and an area of 1.74 hectares, the terrain is the coastal peninsula (Fig. 2). The area was aerially surveyed with a professional-grade UAV. It was compared with GNSS surveyed check points (CPs) via a static surveying method in which a GNSS network from CORS was used to achieve the main objectives of this study. The horizontal and vertical accuracies of ortho-imagery and DSM are crucial for their application in various fields, such as mapping and urban planning. The accuracy levels depend on multiple factors, including data quality, equipment used, and processing techniques.

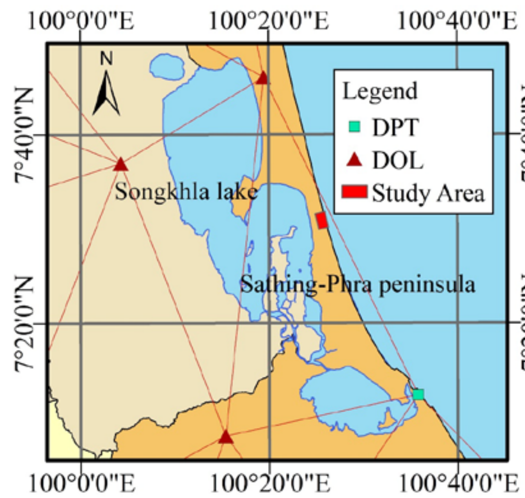

Fig. 2 Study area on the Sathing-Phra peninsula

4.2 Survey Equipment

In this study, the UAV used was a DJI Phantom 4 Pro V.2 quadcopter type, designed and assembled by the DJI company; it was ready to work autonomously, offering a camera, including the FC6310, with a focal length of 8.8 mm. It was equipped with a 1-inch

CMOS sensor and a 20-megapixel resolution. The pixel size should be 2.41 microns on the basis of a sensor size of 13.2 mm × 8.8 mm. The image sensor formats and captures images that are 5472 × 3648 pixels [20]. Mechanical shutters and RGB sensors were utilized in this aerial survey (Fig. 3). Among the GNSS receivers, Stone S10 supports 220 channels, allowing it to receive signals from all major GNSSs. It supports RTK positioning, offering centimetre-level accuracy for horizontal and vertical measurements of the network RTK process via the VRS technique around the study area.

Fig. 3 The UAVs employed in this study

4.3 Field Survey for GCPs and CPs

Ground control points (GCPs) are points within a project area with known coordinates. These coordinates are measured by surveying methods, or are obtained through sources such as the GNSS. In this project, GCP coordinates are acquired via the NRTK to increase the accuracy of the position information of the resulting products. While georeferenced products can be generated without GCPs, it is highly recommended that numerous GCPs be used to produce reliable results. In this project, 8 GCPs were used. The GCPs help ensure that the model is precisely positioned on the Earth's surface. Typically, GCPs are placed along surface edges and at various points within the project area. Additionally, CPs are employed to independently verify the project's accuracy, and are distributed randomly throughout the project area. In total, 33 points, with 8 used as control points, and 25 used as checks, were used to verify the accuracy (Fig. 4). The CPs were measured via the rapid static survey technique with the GNSS network from the Thailand National CORS Data Center (NCDC) and via online postprocessing.

The photogrammetry software, Pix4D mapper, recommends adding at least 8 GCPs to a project to enhance the stability and accuracy of the 3D map. According to the Thailand UAV mapping standard, GCPs are suggested for a square block with a distance not exceeding 500 m to achieve good results for the root mean square error (RMSE) metric. The NRTK method, which uses the VRS technique, was employed to measure the GNSS coordinates of each GCP. Each CP was measured via the rapid static method (Fig. 5) and with postprocessing.

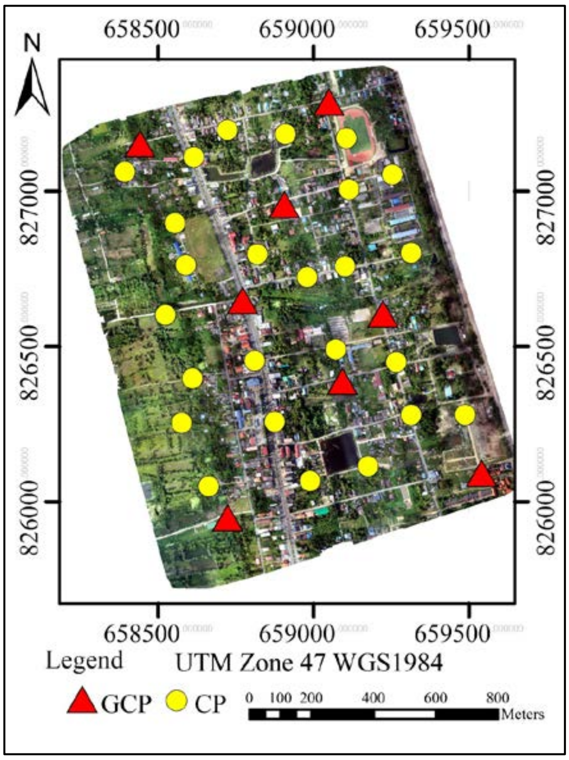

Fig. 4 Map of the GCP and CP locations

Fig. 5 Rapid static GNSS surveying for CPs

4.4 Flight Mission Planning

Mission planning, a comprehensive process, is composed of two main components: a flight map and specifications. The specifications, a detailed guide, and requirements for capturing images include camera settings, scale, flying height, overlap, side-lap, and ground sampling distance (GSD). The GSD, a critical factor that varies with flying height, directly influences the achievable accuracy and the level of detail in the final product. The flight planning for this project was made easy and flexible by the Pix4D capture application, a tool that aids in image acquisition. With this mission planner, numerous parameters can be adjusted to ensure that the UAV captures images with an optimal GSD, resulting in high-resolution output for comprehensive area coverage. The specific parameters for flight planning were as follows: a flying height of 140 m for mapping to achieve an optimal balance between the coverage area and the GSD. At this altitude, the GSD is sufficiently fine, but if the altitude increases, it results in a lower spatial resolution, a forward overlap of 80%, a side overlap of 70%, a GSD of 4.35 cm, a maximum speed of 15 m/s, and a flight time of approximately 50 minutes. Each of these parameters, which play crucial roles, remained constant throughout the mission.

4.5 UAV Image Processing

From the planned flying height and the forward and side overlaps, 660 images were captured. Aerial triangulation was performed via the Pix4D mapper software, which involved importing and tying the images by matching the tie points or critical points between overlapping images, with a median of 5,533 points per image. For further refinement, 8 GCPs were surveyed with NRTK to obtain coordinates in UTM WGS1984 (Table 1).

Table 1. GCPs coordinate in UTM WGS1984

Points NRTK	Northing (m)	Easting (m)	Ortho height (m)
GCP1	825949.600	658900.308	3.453
GCP2	826408.701	658825.650	3.126
GCP3	827097.109	658591.396	3.077
GCP4	827351.268	659256.398	2.061
GCP5	826535.317	659227.662	2.594
GCP6	826918.599	658984.470	2.971
GCP7	826287.155	659299.922	2.705
GCP8	826124.616	659618.076	2.211

Moreover, CPs were imported and measured within the software to adjust the image alignment and enhance the triangular network. The bundle block adjustment (BBA) process included the following steps: number of 2D key-point observations for the BBA: 936,090 points; number of 3D points for the BBA: 314,478 points; and mean reprojection error: 0.089 pixels, which is well within the standard threshold of 0.3 pixels. This meticulous adjustment process ensures high accuracy and precision in the final output.

The 3D coordinate points and mesh are created via the "point cloud and mesh" tool. These points represent coordinates in the Earth's surface or photogrammetry, called a triangulated irregular network (TIN), for use in the generated DSM and ortho imagery. Starting from the known exterior orientation and camera calibration parameters, a scene can be digitally reconstructed through automated dense image-matching techniques [21]. The generated point cloud is then triangulated to form a mesh. The Pix4d mapper generates a DSM and produces an orthophoto of the study area. The GCPs were used for aerial triangulation to provide a 3D model with project georeferencing, achieving an RMS error of 0.011 m. The GCPs were also accustomed to geo-reference images to map projections on the UTM system.

The UAV images result in the creation of a DSM and an ortho-mosaic imagery. This outcome is due to the photogrammetry technique, which considers the surface during aerial triangulation. The generated orthophotos are crucial for assessing accuracy and enhancing visualization. The DSM is beneficial for evaluating the correctness of the elevation values within an area. Spatial analysis uses standard techniques on the generated ortho-mosaic and DSM images. Moreover, measurements are taken using the coordinates of the checkpoints. These checkpoint data are compared with GNSS rapid static survey data to determine the horizontal coordinate errors (Fig. 6), and the mean vertical error is 0.053 m. The standard division is 0.036 across the 25 CPs.

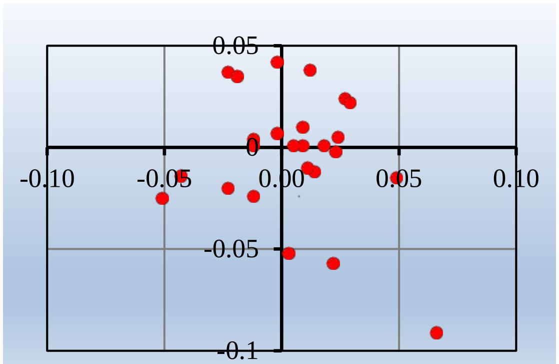

Fig. 6 Distribution of the horizontal error (m)

4.6 Accuracy Assessment

This section discusses reporting spatial data accuracy by various standards, primarily through the National Standard for Spatial Data Accuracy (NSSDA) established by the Federal Geographic Data Committee (FGDC) for geospatial positioning accuracy standards. The accuracy of the existing and legacy spatial data and maps is reported in alignment with the NSSDA or the specific accuracy standard used for their evaluation. It uses the RMSE for the horizontal (r) and vertical (z) coordinates as defined by the ASPRS accuracy standards for large-scale maps. These standards and their relationships with NSSDA and accuracy labelling are detailed to enable users to assess the positional accuracy of spatial data for their applications. The NSSDA standard specifies spatial data accuracy at a 95% confidence level; horizontal refers to Eq. (1), and vertical refers to Eq. (2). The RMSE from three applications is obtained by multiplying the RMSE r by a constant value of 40 to calculate the map scale factor (MSF). According to the ASPRS standard, this factor is calculated via a specific equation. Additionally, the vertical accuracy is used to analyse the contour interval (CI) according to Eq. (3) [22].

$$Horizontal\ ACC = 1.7308 \times RMSEr \quad (1)$$

$$Vertical\ ACC = 1.9600 \times RMSEz \quad (2)$$

$$Vertical\ ACC = 0.5958 \times CI \quad (3)$$

Thailand UAVs Surveying for Engineering standard (TUSE) is a standard for checking positional results to determine that the obtained results have sufficient resolution and accuracy for application in engineering, as specified by the standard. On the basis of the ASPRS positional accuracy standards for digital geospatial data of 2014, this study aims to set and develop standards for positional accuracy, focusing on digital data, including orthophotos and digital elevation models (DEMs). The absolute horizontal accuracy at CE95 refers to the accuracy of a geospatial measurement, specifically the horizontal component. The CE95 value represents the circular error at the 95% confidence level. Pixel size is the physical dimension of a single pixel in an image. The specified requirement ensures that the geospatial accuracy is within a specific range relative to the pixel size and accuracy class X (Table 2).

Table 2. This is an ASPRS accuracy standard [22]

Horizontal Acc. Class X	RMSE xy (cm)	RMSE r (cm)	Horizontal CE95 (cm)
	≤ X×GSD	≤1.41X×GSD	≤ 2.4X×GSD
Vertical Acc. Class X	RMSE z NVE (cm)	NVE CE95 (cm)	Vegetated CE95 (cm)
	≤ X×GSD	≤ 1.96X×GSD	≤ 3.0X×GSD

In the context of UAV surveying, camera accuracy is crucial because it directly impacts the spatial accuracy of the resulting data. This standard categorizes digital cameras on UAVs on the basis of their accuracy into three types: consumer-grade, professional-grade, and survey-grade. These categories consider parameters such as the shutter type, lens type, and sensor size [23], which influence the resolution and precise location of the photo coordinates. For this particular project, a UAV equipped with a professional-grade camera was used. The spatial data accuracy achieved for horizontal ortho-imagery was 2GSD, which translates to approximately 8 cm. The vertical accuracy for the DSM was 3.5GSD, approximately 14 cm (Table 3).

Table 3. Types of digital cameras used for UAV surveys according to the TUSE standards [23]

UAV Camera Type (Grade)	Shutter Type	Sensor Size	Horizontal Accuracy	Vertical Accuracy
Consumer	Rolling	< 1”	5 GSD	6 GSD
Professional	Global	≥ 1”	2 GSD	3.5 GSD
Survey	Global	≥ 1”	2 GSD	3 GSD

5. RESULTS

The UAV photogrammetric output data, including the DSM and orthophoto, were processed via UAV imagery with 8 GCPs surveyed from the NRTK of Thailand's GNSS network, employing the VRS technique. Limiting the UAV's flight speed to less than 10 m/s reduces motion blur, resulting in sharper images and a better spatial resolution. It also increases image overlap, improving the data quality for 3D models and ortho-mosaics. The resulting 3D mapping achieved centimetre-level accuracy, which was verified by comparing it with 25 CP coordinates surveyed via the rapid static GNSS method and postprocessing from the NCDC. The accuracy assessment revealed a horizontal RMSE of 4.04 cm and a vertical RMSE of 6.35 cm. A map that depicts the spatial distributions of the horizontal error (Fig. 7) and vertical error (Fig. 8) is created. The horizontal RMSE of the ortho-mosaic imagery with an NSSDA confidence level of CE95 at 6.99 cm, or approximately 1.7GSD, is classified as horizontal accuracy class I. The vertical RMS error of the DSM with a CE95 of 12.44 cm, or approximately 3.1GSD, is classified into vertical accuracy class II as the standard (Table 4).

Table 4. Spatial accuracy compared with that of TUSE

Avg. GSD 4.35 cm.	Horizontal	Accuracy (CE95) (cm)	Vertical Accuracy (CE95) (cm)	
TUSE	8.70	2 GSD	15.22	3.5 GSD
Results	6.99	1.7 GSD	12.99	3.1 GSD
Status		Accepted		Accepted
Accuracy Class		I		II

The map scale factor (MSF), following the ASPRS 2014 standard, can be produced at a maximum scale of 1:160. This accuracy level is suitable for drafting, construction work, and survey design. The vertical accuracy must be sufficient to detect the elevation changes at contour intervals of 20 cm.

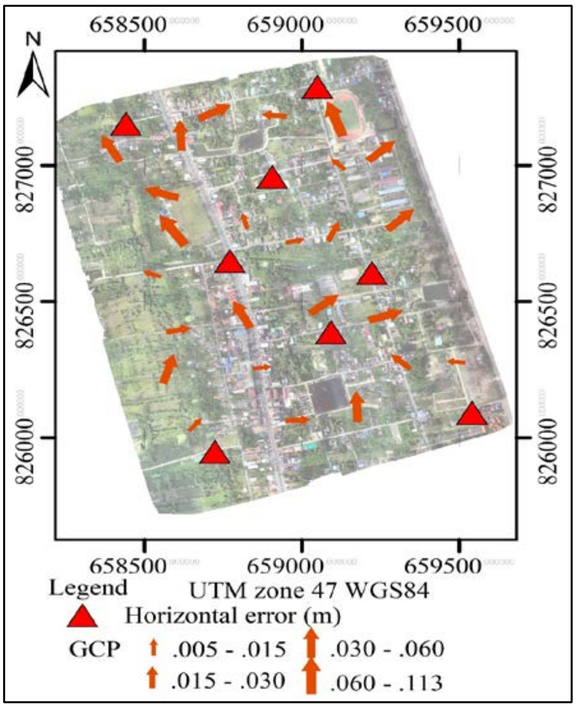

Fig. 7 Map of the distribution of the horizontal error

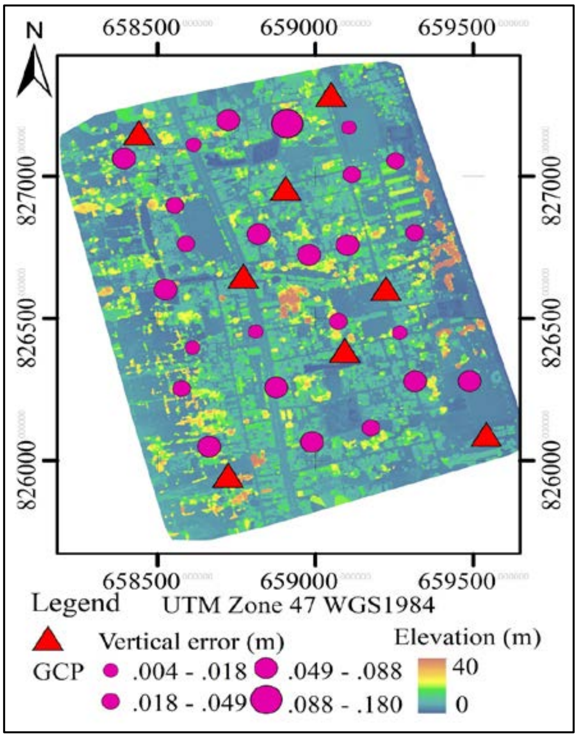

Fig. 8 Map of the distribution of the vertical error

6. CONCLUSIONS

The application of the RTK GNSS network for GCPs in UAV surveys with the photogrammetry process in the Sathing-Phra subdistrict confirms the importance of accurate georeferencing to achieve sufficiently precise results. This paper provides an overview of the use and spatial accuracy of NRTK with UAV mapping, complementing digital photogrammetry. However, a thorough point cloud analysis is also necessary to ensure high quality and reliability. The geometry of GCP and image acquisition impacts the precision of photogrammetry. Nonetheless, professional-grade UAVs offer a robust platform and real-time GNSS service capable of supporting accurate aerial mapping. The terrain of the selected study area varies for the 25 CPs, including coastal regions, encompassing the entire study area. In this project, using the GNSS rapid static method for CPs, the photogrammetric spatial data products, including ortho imagery and DSM, achieved a horizontal accuracy of 6.99 cm and a vertical accuracy of 12.44 cm. Most monitoring points clustered together with errors close to zero. This study demonstrates that low-cost UAV photogrammetry can produce highly accurate and high-resolution results, with a horizontal accuracy of 1.7 GSD and a vertical accuracy of 3.1 GSD, both of which meet TUSE standards. According to the ASPRS 2014 standard, the MSF allowed for a maximum scale of 1:160, providing horizontal accuracy suitable for class I and applicable for drafting, construction, and survey design. The vertical accuracy supports producing a contour interval of up to 20 cm, class II, the second-highest vertical accuracy class, which could pertain to local or network accuracy.

This finding aligns with research on the accuracy of GNSS CORS via the VRS method and static GNSS measurements for topographic maps in Turkey, where NRTK methods demonstrated similar deviations. In Thailand, compared to research on the accuracy of DSMs obtained from UAV photogrammetry via GCPs through static surveys, the horizontal error does not exceed ±3.0 cm, and the vertical error does not exceed ±1.0 m [24]. Additionally, it was observed that GCPs obtained via static surveys are slightly more accurate than those obtained through NRTK, with differences of less than 5 cm, which is sufficient for applications such as urban planning. A limitation of this project is the lack of more diverse terrain, such as mountains and rivers. Additionally, the UAV must fly at higher altitudes to avoid signal loss, which leads to higher GSD values. The distance from the study area to the CORS station is a critical factor in NRTK accuracy. In future studies, a wider range of areas and elevations will be selected, and adding more CORS stations will further improve NRTK accuracy.

The integration of Thailand's GNSS RTK network into the national CORS will facilitate easier access to high-precision coordinates. This integration is particularly useful for aerial surveys with UAVs and can be applied to 3D urban simulations, environmental planning, city modeling, and disaster situation modeling. Furthermore, the spatial data from this research can be imported into open-source programs for presentation in an online WEB GIS system at http://www.bit.ly/Songkhlalake_UAV, enabling local agencies to use the data for urban and agricultural planning.

7. ACKNOWLEDGEMENTS

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