

Article

Mapping Gaps in Sugarcane Fields Using UAV-RTK Platform

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Abstract: Unmanned aerial vehicles (UAVs) equipped with a global real-time kinematic navigation satellite system (GNSS RTK) could be a state-of-the-art solution to measuring gaps in sugarcane fields and enable site-specific management. Recent studies recommend the use of UAVs to map these gaps. However, low-accuracy GNSS provides incomplete or inaccurate photogrammetric reconstructions, which could easily generate an error in the gap measurement and constrain the applicability of these techniques. Therefore, in this study, we evaluated the potential of UAV RTK imagery for mapping gaps in sugarcane. To compare this solution with conventional UAV approaches, the precision and accuracy of RTK and non-RTK flights were evaluated. To increase the robustness of the research, flights were performed to map gaps found naturally in the field and with plants at different stages of development. Our results showed that the lengths of gaps identified by both RTK and non-RTK UAV imagery were similar, with differences in precision and accuracy of about 1% for both systems. In contrast, RTK was much more efficient and provides stakeholders with guidelines for accurate and precise mapping gaps, allowing them to make confident decisions on site-specific management.

Keywords: sugarcane gaps; UAV-RTK; plant height; positional accuracy; site-specific management



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1. Introduction

Sugarcane (*Saccharum* spp.) is the major crop used for producing sugar, bioethanol, and bioenergy, making it the main commodity for the economy [1]. Globally, Brazil, India, and China are the largest producers of the crop, collectively producing around 2 billion tons of sugarcane per year [2]. Sugarcane is a semi-perennial crop, and generally 12 months after planting, the crop is ready to be harvested and sent for industrial processing. After the harvest, the vegetative part (ratoon) that remains in the soil gives rise to new sprouts and starts a new season. In the past, sugarcane could support up to 10 harvests from the first planting; nowadays, only 3–5 harvests are possible [3]. This is due to the intensification of mechanized harvesting processes, which damage and shake the ratoon and compact the soil, negatively affecting the longevity of the sugarcane plantation and increasing the number of gaps in the crop rows [3–7].

Gaps in sugarcane are defined as empty spaces between stalks larger than 0.50 m [8]. Although they are undesirable, even the most technologically advanced sugarcane fields have an average of 20% gaps [8]. Therefore, identifying gaps in the field is important and can help producers make decisions regarding replanting, field renovation, yield estimation, and even site-specific management. By searching the scientific literature, we found promising studies that used sophisticated techniques to identify gaps in sugarcane by combining unmanned aerial vehicle (UAV) imagery and photogrammetric techniques. For instance, in the approach proposed by Luna and Lobo [9], the authors used a photointerpretation method using RGB UAV imagery as an alternative to traditional field measurement methods. The results showed high precision ($R^2 = 0.9$) and high accuracy (RMSE = 5.04). In an

investigation by Souza et al. [10], the authors used images captured by UAV with spectral filters for green, red, and NIR. The images were processed using the object-based image analysis (OBIA) technique, and the results of the gaps measured in the field were compared with the gaps estimated from the images with an accuracy of 0.97. Further searching of the literature led us to that of Barbosa Júnior et al. [11]. In their study, the authors used RGB UAV images for gap estimation and designed the best mapping strategies by combining the best flight height and the best stage of plant development stage. So far, these are the most complete and accurate results in the literature ($R^2 = 0.97$, absolute error = 0.015 m). Overall, the studies presented above are relevant and contribute to addressing problems in gap mapping. However, they are still limited in their application. Since gap mapping allows for replanting decisions and site-specific actions, positional accuracy is the key to the applicability of the analyzed results. However, existing gap mapping studies have not yet focused on this aspect.

Photogrammetric processes are used to construct surface models and represent objects in the field. However, a low-accuracy GNSS makes it susceptible to distortions and georeferencing errors [12]. For conventional GNSSs, displacement and scale errors are more likely to occur, resulting in measurement errors and inaccurate proportions in the reconstructed model [13]. In addition, the number of images or the limitations in their positions result in more occluded areas and ambiguous features. This could result in incomplete or inaccurate reconstructions of the sugarcane gaps. Therefore, investigations using high-precision and high-accuracy positional systems are necessary to guarantee fully usable gap results. Typical approaches to support better positional information for UAVs include ground control points (GCPs), post-processed kinematic correction (PPK), and real-time kinematic correction (RTK) devices [14,15]. All these systems have been investigated in terms of accuracy, and it is clear that they can address the positioning requirement by achieving centimetric accuracy [16–19]. However, to the best of our knowledge, no study has investigated whether the GNSS accuracy affects the photogrammetric reconstruction and therefore influences the sugarcane gap length.

Therefore, in this study, we present an innovative proposal in mapping gaps in sugarcane. We used a UAV with both RTK and non-RTK systems to capture images in sugarcane fields at different phenological stages and consequently generate maps of gaps. The results of the two systems were compared and validated against field observations.

2. Materials and Methods

2.1. Environment of Study

This study was carried out in sugarcane fields in the countryside of São Paulo state, Brazil (Figure 1). We conducted our study in five fields. The climatic conditions and soil type are similar: Aw climate with dry winter, average temperature of 23 °C and precipitation of 1400 mm [20]; and oxisol-type soil with clay texture and low slope [21]. The study fields were cultivated with sugarcane cultivars, and to fit our first objective, had plants of different heights. More details of the environments of study are provided in Table 1.

Table 1. Sugarcane cultivars grown in the environments of study.

Field ID	Cultivar Name	Ratton	Date of Harvest	Yield (t ha ^{−1})
NEI-16	CTC 9005	4°	15 April 2022	100
TIJ-03	RB 85-5156	4°	15 April 2022	85
MTA-11	IAC SP 91-1099	2°	15 May 2022	80
FSI-46	CTC 22994	1°	15 June 2022	120
FMB-01	RB 85-5156	5°	3 July 2022	95

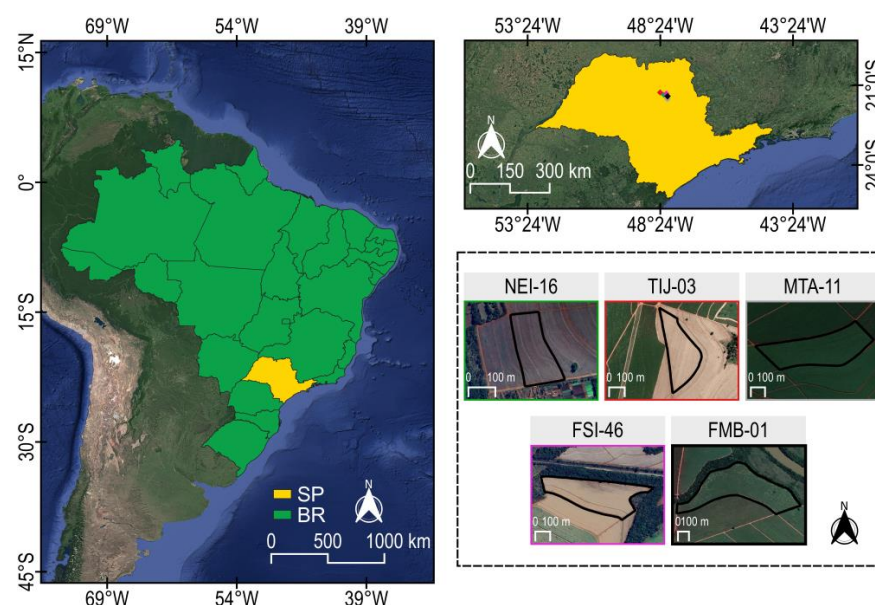


Figure 1. Brazil map highlighted on the **left**. São Paulo state in the **upper-right** corner. Sugarcane fields in the **lower-right** corner.

2.2. In Situ Measurement

We measured 25 gaps equally distributed over five crop rows in each of the sugarcane fields (Table 1). The measured gaps were randomly selected within the row, considering a minimum gap size of 0.50 m [9]. All gaps in the field were individually identified by a marker for later comparison with the gaps measured by the images. Additionally, to characterize the fields, we measured the height of 20 plants randomly distributed in the field.

2.3. UAV Image Acquisition

2.3.1. Unmanned Aerial Vehicle and Flight Mission

A multi-rotor UAV (DJI Phantom 4 Multispectral RTK, Shenzhen, China) was used for the image acquisition. The UAV has a camera onboard fixed by a 3-axis gimbal. The camera has a focal length of 5.74 mm, an image size of 1600×1300 pixels, and a sensor size of $4.87 \text{ mm} \times 3.69 \text{ mm}$. The camera has six image sensors: five multispectral sensors and one RGB sensor. In our study, we used only the RGB images. The flight mission was performed automatically by an application (DJI GS Pro, Shenzhen, China) on 5 August 2022. Images were captured with gimbal at -90° angle, image overlap of 70%, flight speed of 7 m/s and flight height of 70 m. In each field, we performed two flights, one flight with RTK link and the other without RTK link, to analyze the impact of positional accuracy in mapping sugarcane gaps. UAV data and flight specifications are presented in Table 2.

Table 2. Timeline of UAV data collection and flight specification.

Field ID	GNSS	Flight Time	Number of Images	GSD (cm)
FSI-46	RTK	08:52–08:59	63	4.15
	non-RTK	09:01–09:07	63	4.08
NEI-16	RTK	09:35–09:39	41	3.72
	non-RTK	09:40–09:44	41	3.78
FMB-01	RTK	10:20–10:25	66	3.68
	non-RTK	10:28–10:32	66	3.73
MTA-11	RTK	10:56–11:00	41	3.68
	non-RTK	11:02–11:06	41	3.80
TIJ-03	RTK	13:50–13:54	40	3.77
	non-RTK	13:55–14:00	40	3.90

2.3.2. Global Navigation Satellite System

This UAV is equipped with a multi-frequency GNSS receiver (DJI D-RTK2 base station, Shenzhen, China) capable of receiving GPS (L1/L2), GLONASS (L1/L2), BeiDou (B1/B2), and Galileo (E1/E5a) signals. To ensure high-precision positioning, the receiver requires a first-fixed time of less than 50 s. This prompt acquisition time guarantees a horizontal accuracy of 1.0 cm and vertical accuracy of 1.5 cm, both with +1 ppm. It is important to note that for every 1 km of movement from the UAV, the positioning error increases by 1 mm. Conversely, when the RTK functionality is disabled, the positioning of the error increases to 0.5 m vertically and 1.5 m horizontally. Moreover, the GNSS supports a high data collection frequency of up to 10 Hz, enabling for the acquisition of accurate position updates at a rapid rate. The UAV can operate in multiple modes, including (i) simple GNSS mode for basic positioning, (ii) RTK mode using the DJI D-RTK2 base station for real-time kinematic corrections, (iii) network RTK mode, which relies on an NRTK service provided for correction data, and (iv) PPK mode, which utilizes raw satellite observations recorded during the flight for post-flight analysis and positioning.

2.4. Photogrammetric Data Processing

To correct occlusion errors and distortions, the images were stitched using Structure from Motion (SfM) software (Agisoft Metashape Professional 1.5.5, Agisoft, St. Petersburg, Russian). The software analyzes images and identifies homologous points between them to simultaneously adjust the positions, orientations, and locations of 3D points. This process attempts to find the best alignment to minimize the differences between the projected features and their observed positions in the images. Based on these results, it is possible to estimate the positional accuracy of the images by analyzing the residuals or errors in the fitting process. The residuals represent the differences between the observed image positions of the key points and their corresponding projections of the optimized image positions and orientations. The magnitude of these residuals provides an indication of the quality and accuracy of the image positions. The main product generated by SfM processing is orthomosaic, which—besides containing the real dimensions of the objects—is also represented in a geographic coordinate system. In our study, we had 10 sets of images (5 RTK and 5 non-RTK). Both sets of images were processed using the same parameters (Table 3) to generate a total of 10 orthomosaics.

Table 3. Agisoft Metashape settings used for stitch images.

Setting		Value
Align Photos	Accuracy	High
	Key point limit	40,000
	Tie point limit	4000
	Projection	Geographic
DEM	Coordinate system	WGS 84/UTM zone 22S (EPSG::32722)
	Source data	Sparse cloud
	Interpolation	Enable (default)
Orthomosaic	Surface	DEM
	Blending mode	Mosaic (default)
	Enable hole filing	√
(Settings not detailed above were kept at default).		

2.5. Image Gap Measurement

When the orthomosaics were generated, the next step was to measure the gaps by the images. For this task we used the open-source package “FIELDImageR” [22] in the R programming language. The step-by-step procedure for measuring the gaps is illustrated in Figure 2 and described below.

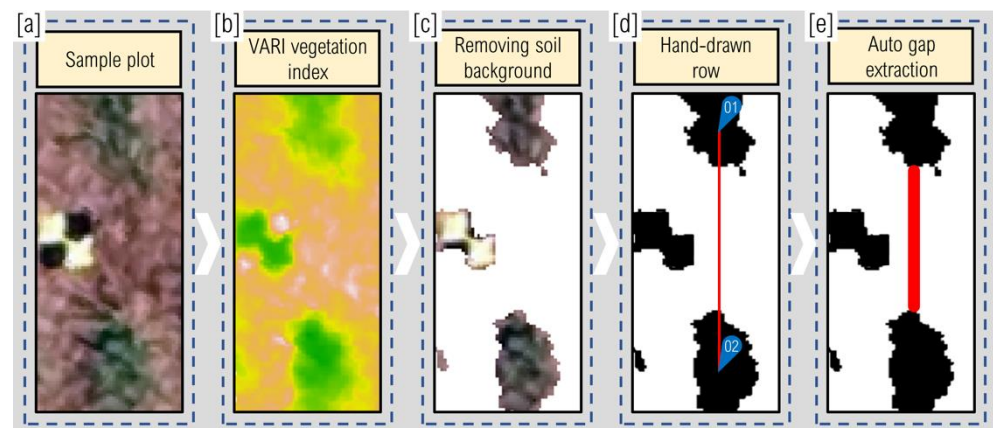


Figure 2. Step-by-step process to measure the gap length by imaging.

- (a) Sample plot: we cut out the region of each gap and form our dataset to analyze each gap independently.
- (b) Vegetation index: on each gap image, we apply the visible atmospherically resistant index (VARI) to differentiate between soil and plant.
- (c) Segmentation: we assigned a VARI value of -0.12 . Image regions with values higher than -0.12 represented the plants, while values lower than this represented the ground background and were automatically removed.
- (d) Gap measurement line: we used the fieldDraw function to create a measurement line. Thus, we clicked on the center of mass of the plants (01 and 02) to create a measurement line.
- (e) Gap length: the fieldDraw function removes the part of the line over the plants, with only the line over the gap remaining. Since the image is geographically specialized, the line length correctly describes the visible length of the gap.

2.6. Data Validation

Firstly, we plotted the gap lengths measured from the images and compared them to the gaps measured in the field. This strategy allowed us to analyze the effects of image-based gap measurement as a function of plant height in the fields and under the GNSS used. We used metrics such as correlation coefficient (R^2) and mean absolute percentage error (MAPE). Secondly, we compared the average image position error between RTK and non-RTK flights that was provided by the SfM software used in this study.

3. Results

3.1. Plant Height Characterization

The study fields were characterized by plant height. As expected, the fields had different plant height conditions (Figure 3). In the first field (FMB-01), plants had an average height of 0.35 m, which is typical at the sprouting stage. Although measurements were performed approximately 30 days after harvest, due to climatic conditions (lack of regular rainfall and high temperatures), the plants were still small. In the second field (FSI-46), plants were slightly taller than in the first field (0.44 m), but still at the sprouting stage. Taller plant heights were observed in the fields more than 60 days after harvest. In field MTA-11, the plants were at the tillering stage, averaging 0.66 m in height. As for field TJI-03, the plants were heading towards the elongation stage and the average height increased to 0.95 m, and NEI-16 was the field with the tallest plants (1.07 m). We noted little variation within each plant height data collection, so we chose to represent our study fields based on average plant height values and subsequently define the best flight option for a plant height-based gap mapping.

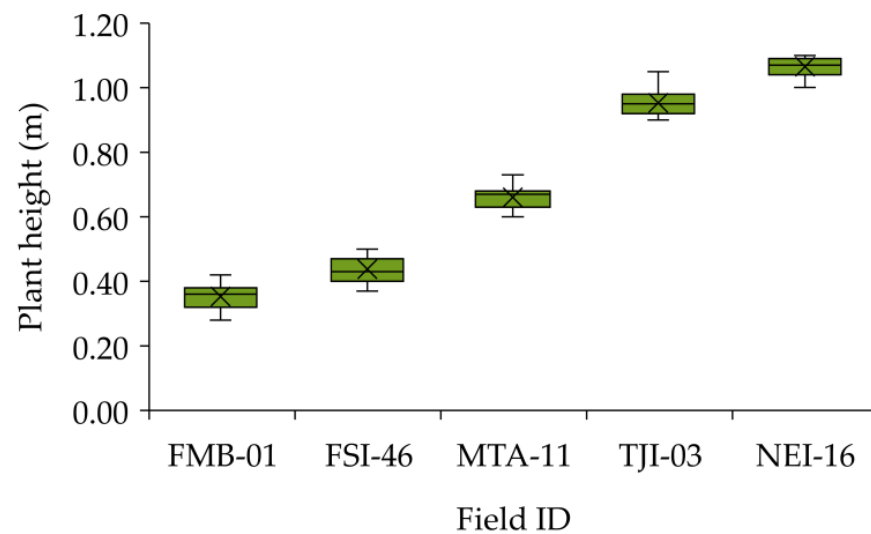


Figure 3. Plant height per sugarcane field. Each box was constituted by 20 values of plant height and represents one field.

3.2. Gap Measurement by UAV GNSSs

Gaps measured in the field were compared to those measured by images collected from both RTK and non-RTK systems (Figure 4). When analyzing the gaps measured by the UAV images, we can note that—regardless of whether the system was RTK or non-RTK—the results were very similar across the five study fields. Precision and accuracy metrics proved to be useful in explaining the proposed approach. On average, the GNSSs differed by less than 2% in both accuracy and precision. However, the key element impacting the results was undoubtedly the height of the plants. We achieved our best result in a combination of precision and accuracy ($R^2 = 0.78$ and $\text{MAPE} = 1.15\%$) when the plants were 0.36 m tall. When the plants were slightly taller (0.44 m), the precision of the results remained high, but the accuracy declined by more than 20%. The fit of the results maintained the same pattern for the other plant heights until reaching the lowest precision and accuracy ($R^2 = 0.57$ and $\text{MAPE} = 61.68\%$) when the plants were tallest (1.07 m). Upon critical analysis of our results, we observed a few overestimated values in gap identification by images, possibly when the plants were smaller. Generally, an increase in plant height allowed underestimation of the gaps measured by the images up to the point where some gaps smaller than 0.70 m were no longer identified.

3.3. GNSS Errors

Thus far, both RTK and non-RTK systems applied to gap mapping by UAV imagery had produced similar results. However, when analyzing the results with regard to the geographical positioning of the images captured by the two systems, significant differences were observed (Figure 5). When flights were performed with the RTK system, image location errors were a couple of millimeters. On average, the planimetric errors (X and Y) were 0.22 mm, while altimetric errors were larger ($Z = 3.25$ mm). Conversely, when using the non-RTK system, errors were on the centimeter scale with image localization errors in X, Y, and Z being constant. On average, the error values were 8.59 cm. Comparing the accuracy of the flights with RTK, variations in image localization among the five flights were 3.2% for X, 5.9% for Y, and 34.5% for Z. In contrast, the non-RTK system proved to be unstable for georeferenced image acquisition, with variations in X reaching 53.3%, in Y 64.5% and in Z a staggering 279%.

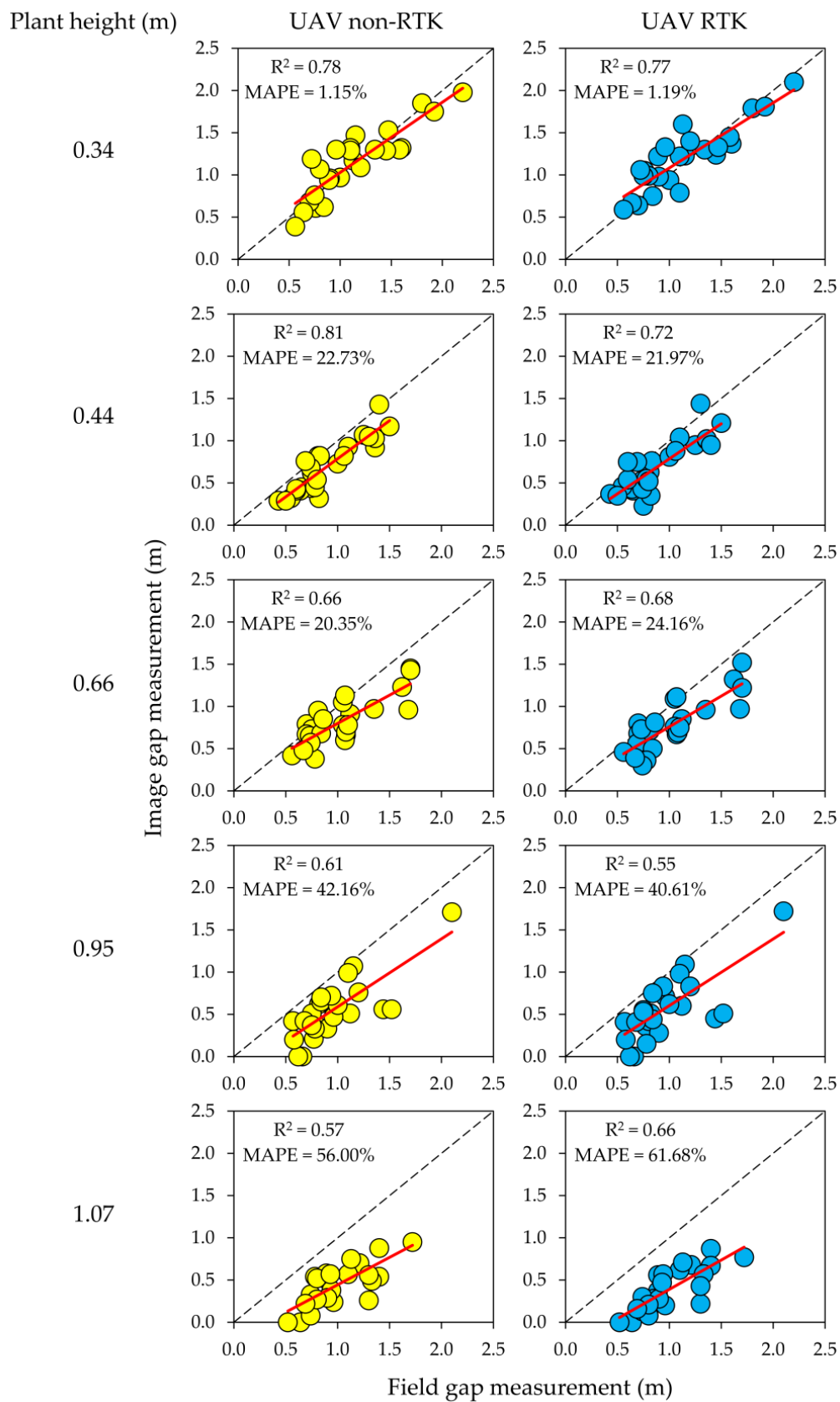


Figure 4. Comparison of field gap measurement and image gap measurement by UAV non-RTK and UAV RTK under plant height.

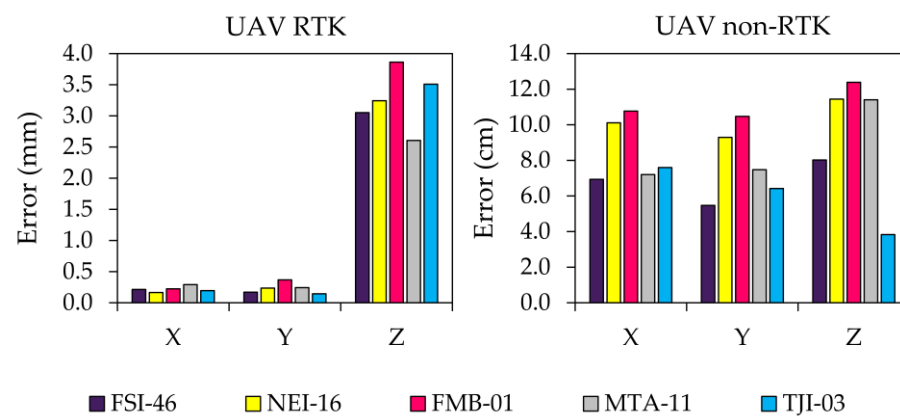


Figure 5. Average camera location error of UAV RTK and UAV non-RTK. X—longitude, Y—latitude, Z—altitude.

4. Discussion

In this study, we used UAV imagery to map sugarcane gaps in five fields and analyzed the effects of flight operation with RTK and non-RTK GNSSs. Previous studies brought consistent results regarding UAV applications in mapping sugarcane gaps. However, the impacts if we use UAV with RTK system for image capture were not known. Therefore, in this study we were able to bring solid results and how GNSS from the UAV can interfere in the mapping of sugarcane gaps.

4.1. Measuring the Gap Length: How Could the Plant Height Act on the Mapping?

Measuring gaps in sugarcane fields is a useful practice for better understanding the condition of the field. Initially, farmers focused on identifying gaps to make decisions about renovation and replanting the sugarcane field. More recently, practices such as site-specific management have become more prevalent to avoid wasting inputs by applying them where no plants exist. Since the introduction of UAVs, gap mapping has become one of the most active topics in sugarcane research [1]. UAVs have been the main platform for gap mapping, and various studies have explored different ways in which the platform can accurately map gaps in sugarcane fields. The main studies for gap mapping gap applied discriminant analysis techniques [9], object-based analysis [10], and a combination of flight height and plant phenology [11]. While the results were able to address some of the problems of gap mapping, they were only partially successful. In order to achieve the promises of gap mapping, such as replanting and/or localized application of inputs, more research is needed.

Firstly, in this study, we used both RTK and non-RTK systems to fly a UAV and map gaps in sugarcane fields with different plant heights. Our results showed that plant height was a critical factor affecting the accuracy of gap mapping. Specifically, the field with smaller plants (0.34 m) produced more accurate and precise results, while the taller plants overestimated gap values. Approximately 50% of the gaps measured by imagery had higher values than the field gaps, whether measured using RTK or non-RTK systems. When sugarcane fields are still at sprouting stage, mapping gaps using a UAV can be unreliable and risky. This is because the challenges of differentiating between plant and soil are greater when plants are very small. In such cases, we should invest in ultra-resolution sensors to capture more accurate images, which is costly. Moreover, some sprouts might not have emerged yet, making estimation unsuccessful. The tillering stage (when plants reach a height of around 0.5 m) is the best time to map gaps reliably, since most sprouts have emerged and challenges of differentiating between plant and soil are reduced. However, as the crop reaches the elongation stage, the accuracy and precision of mapping rapidly decreases due to development of the leaf canopy, which covers the gaps [11]. Therefore, mapping gaps becomes a critical task at this stage.

4.2. Measuring the Gap Length: Should We Use UAV RTK or Non-RTK?

Identifying gaps in sugarcane and determining their location is essential to achieving mapping objectives. Our study demonstrated that both RTK and non-RTK systems effectively measured length of gaps. However, the primary challenge lies in accurately positioning the gaps on the map. Nowadays, the ability to address localized issues is a critical aspect of field technologies. If we can map gap locations in sugarcane fields, we could potentially develop an automated seedling replanting system. In cases where this proves impossible, it would be beneficial to avoid applying inputs on the gaps. On average, even sugarcane fields with advanced technology still have 20% gaps [8]. Therefore, not applying inputs to these gaps would have a positive economic impact.

Our results showed that images captured by UAV using both RTK and non-RTK systems for sugarcane gap mapping could measure gap length in a similar way. These findings are important and pave the way for the application of a cost-effective GNSS on UAVs in sugarcane gap mapping, although with some restrictions. Due to the low altitude of UAV flights, a single image cannot cover the entire area of interest. Flight techniques are therefore used to capture multiple overlapping images, which are later merged into a single orthomosaic using photogrammetric reconstruction [23]. The main requirement is that the images have homologous points, meaning that multiple images have captured the same object and have a geographic position so that it can be represented on a map [23]. Additionally, low-accuracy GNSS can introduce distortions during the photogrammetric process [12]. However, our results demonstrated that the GNSS was not a significant factor.

Assessing the average location errors of images is the only accuracy measure when no GCPs are used [24]. In our study, we used UAV RTK, and the results were consistent with errors in the millimeter range and little variation. However, when the non-RTK system was used, the data were highly unstable, with incredible variation in image localization. Therefore, we could conclude that using the UAV RTK would be the best option. Interestingly, both GNSSs had larger vertical errors than horizontal errors, which has also been observed in previous studies [25–27]. The authors suggested that this is due to possible miscalculations of the camera's internal parameters in the autocalibration process, which would be a recurring problem for non-metric cameras [25].

5. Conclusions

Advances in UAV RTK imagery provide a valuable opportunity for producing finely detailed maps of gaps in sugarcane. This study used these data sources to investigate different strategies for mapping gaps, using either RTK or non-RTK data, at different crop development stages. The results showed that plant height could significantly affect the mapping of gaps in sugarcane using UAVs. To avoid overestimating the results when plants are small or underestimating them when the plants are tall, it is necessary to perform mapping precisely at the exact moment of crop development. The use of RTK or non-RTK data for mapping neither affected the identification nor the length of the gaps. However, RTK showed greater precision and accuracy in determining the geographic location of the gaps. Consequently, the use of RTK is imperative for mapping gaps in sugarcane for site-specific management.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

DEM	digital elevation model
GCPs	ground control points
GNSS	global navigation satellite system
MAPE	mean absolute percentage error
NRTK	network real-time kinematic
OBIA	object-based image analysis
PPK	post-processed kinematic
RMSE	root-mean-square error
RTK	real-time kinematic
SfM	structure from motion
UAVs	unmanned aerial vehicles
VARI	visible atmospherically resistant index

References

- Barbosa Júnior, M.R.; Moreira, B.R.A.; Brito Filho, A.L.; Tedesco, D.; Shiratsuchi, L.S.; Silva, R.P. UAVs to Monitor and Manage Sugarcane: Integrative Review. *Agronomy* **2022**, *12*, 661. [\[CrossRef\]](#)
- Shahbandeh, M. *Sugar Cane Production Worldwide—Forecast 2016–2026*; Statista: Hamburg, Germany, 2022.
- Molin, J.P.; Veiga, J.P.S. Spatial Variability of Sugarcane Row Gaps: Measurement and Mapping. *Ciênc. Agrotecnol.* **2016**, *40*, 347–355. [\[CrossRef\]](#)
- Santos, M.A.L.; Silva, S.; Zocoler, J.L.; Teodoro, I.; Dantas Neto, J.; Sousa, J.d.S. Avaliação de Falhas Na Brotação Da Cana-de-Açúcar Em Função Da Disponibilidade Hídrica. *Agropecu. Cient. No Semiárido* **2013**, *9*, 30–35.
- Matsuoka, S.; Stolf, R. Sugarcane Tillering and Ratooning: Key Factors for a Profitable Cropping. In *Sugarcane: Production, Cultivation and Uses*; Nova Publishers: Hauppauge, NY, USA, 2012; pp. 138–157. ISBN 9781612097459.
- Raper, R.L. Agricultural Traffic Impacts on Soil. *J. Terramech.* **2005**, *42*, 259–280. [\[CrossRef\]](#)
- Zhao, P.; Guo, J.; Gao, X.; Liu, G.; Li, Y.; Burner, D.M.; Yang, L. Small-Scale Mechanical Harvesting and Tractor-Caused Soil Compaction Reduce Early Growth in Sugarcane. *Agronomy* **2019**, *9*, 830. [\[CrossRef\]](#)
- Stolf, R. Methodology for Gap Evaluation on Sugarcane Lines. *STAB* **1986**, *4*, 12–20.
- Luna, I.; Lobo, A. Mapping Crop Planting Quality in Sugarcane from UAV Imagery: A Pilot Study in Nicaragua. *Remote Sens.* **2016**, *8*, 500. [\[CrossRef\]](#)
- Souza, C.H.W.; Lamparelli, R.A.C.; Rocha, J.V.; Magalhães, P.S.G. Mapping Skips in Sugarcane Fields Using Object-Based Analysis of Unmanned Aerial Vehicle (UAV) Images. *Comput. Electron. Agric.* **2017**, *143*, 49–56. [\[CrossRef\]](#)
- Barbosa Júnior, M.R.; Tedesco, D.; Corrêa, R.G.; Moreira, B.R.A.; Silva, R.P.; Zerbato, C. Mapping Gaps in Sugarcane by UAV RGB Imagery: The Lower and Earlier the Flight, the More Accurate. *Agronomy* **2021**, *11*, 2578. [\[CrossRef\]](#)
- Psiroukis, V.; Papadopoulos, G.; Kasimati, A.; Tsoulas, N.; Fountas, S. Cotton Growth Modelling Using UAS-Derived DSM and RGB Imagery. *Remote Sens.* **2023**, *15*, 1214. [\[CrossRef\]](#)
- Deliry, S.I.; Avdan, U. Accuracy of Unmanned Aerial Systems Photogrammetry and Structure from Motion in Surveying and Mapping: A Review. *J. Indian Soc. Remote Sens.* **2021**, *49*, 1997–2017. [\[CrossRef\]](#)
- Amaral, L.R.; Zerbato, C.; Freitas, R.G.; Barbosa Júnior, M.R.; Simões, I.O.P.S. UAV Applications in Agriculture 4.0. *Rev. Ciênc. Agron.* **2020**, *51*, 1–15. [\[CrossRef\]](#)
- Amaral, L.R.; Freitas, R.G.; Barbosa Júnior, M.R.; Simões, I.O.P.d.S. Application of Drones in Agriculture. In *Digital Agriculture*; Springer International Publishing: Cham, Switzerland, 2022; pp. 99–121. [\[CrossRef\]](#)
- Martínez-Carricondo, P.; Agüera-Vega, F.; Carvajal-Ramírez, F. Accuracy Assessment of RTK/PPK UAV-Photogrammetry Projects Using Differential Corrections from Multiple GNSS Fixed Base Stations. *Geocarto Int.* **2023**, *38*, 2197507. [\[CrossRef\]](#)
- Nwilag, B.D.; Eyoh, A.E.; Ndehedehe, C.E. Digital Topographic Mapping and Modelling Using Low Altitude Unmanned Aerial Vehicle. *Model. Earth Syst. Environ.* **2023**, *9*, 1463–1476. [\[CrossRef\]](#)
- Famiglietti, N.A.; Cecere, G.; Grasso, C.; Memmolo, A.; Vicari, A. A Test on the Potential of a Low Cost Unmanned Aerial Vehicle RTK/PPK Solution for Precision Positioning. *Sensors* **2021**, *21*, 3882. [\[CrossRef\]](#)
- Iizuka, K.; Ogura, T.; Akiyama, Y.; Yamauchi, H.; Hashimoto, T.; Yamada, Y. Improving the 3D Model Accuracy with a Post-Processing Kinematic (PPK) Method for UAS Surveys. *Geocarto Int.* **2022**, *37*, 4234–4254. [\[CrossRef\]](#)

20. Alvares, C.A.; Stape, J.L.; Sentelhas, P.C.; Gonçalves, J.L.M.; Sparovek, G. Köppen's Climate Classification Map for Brazil. *Meteorol. Z.* **2013**, *22*, 711–728. [[CrossRef](#)]
21. Rossi, M. *Mapa Pedológico do Estado de São Paulo: Revisado e Ampliado*; Instituto Florestal: São Paulo, Brazil, 2017; Volume 1, ISBN 9788564808164.
22. Matias, F.I.; Caraza-Harter, M.V.; Endelman, J.B. FIELDimager: An R Package to Analyze Orthomosaic Images from Agricultural Field Trials. *Plant. Phenome J.* **2020**, *3*, e20005. [[CrossRef](#)]
23. Gilliot, J.-M.; Hadjar, D.; Michelin, J. Potential of Ultra-High-Resolution UAV Images with Centimeter GNSS Positioning for Plant Scale Crop Monitoring. *Remote Sens.* **2022**, *14*, 2391. [[CrossRef](#)]
24. Masný, M.; Weis, K.; Biskupič, M. Application of Fixed-Wing UAV-Based Photogrammetry Data for Snow Depth Mapping in Alpine Conditions. *Drones* **2021**, *5*, 114. [[CrossRef](#)]
25. Štroner, M.; Urban, R.; Reindl, T.; Seidl, J.; Brouček, J. Evaluation of the Georeferencing Accuracy of a Photogrammetric Model Using a Quadcopter with Onboard GNSS RTK. *Sensors* **2020**, *20*, 2318. [[CrossRef](#)] [[PubMed](#)]
26. Forlani, G.; Diotri, F.; di Cella, U.M.; Roncella, R. Indirect UAV Strip Georeferencing by On-Board GNSS Data under Poor Satellite Coverage. *Remote Sens.* **2019**, *11*, 1765. [[CrossRef](#)]
27. Benassi, F.; Dall'Asta, E.; Diotri, F.; Forlani, G.; Morra di Cella, U.; Roncella, R.; Santise, M. Testing Accuracy and Repeatability of UAV Blocks Oriented with GNSS-Supported Aerial Triangulation. *Remote Sens.* **2017**, *9*, 172. [[CrossRef](#)]

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