# Aspects of Quality Control for UAV Applications in Photogrammetry

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**Key words**: 3D test field, camera sensors, georeferencing, GNSS-RTK, multi-sensor system, quality control, UAV

## SUMMARY

In the underlying work, the components for surveying projects using UAV are described and their influence on the quality of the results is analysed. From a geodetic-photogrammetric point of view, the focus is on measuring sensors (camera, laser scanner, GNSS) as well as on resulting measurement data and their processing by utilising suitable software. For testing (and, if necessary, calibration) of the mentioned sensors, the use of 3D test fields with a correspondingly large number of signalised ground control points (GCP) is an appropriate practice. These test fields allow an evaluation of the photogrammetric processes as well as the involved components (sensors). Currently, imaging sensors (cameras) are the preferred measurement tool for UAV measurements, although laser scanners are being increasingly used on UAV platforms. Here, the performance of two UAV systems which are frequently used in geodetic surveying projects, has been tested through corresponding test field flights, in particular in interaction with the process component "RTK-GNSS" for the determination of the sensor positions. Finally, recommendations for the combined use of GCP and precise RTK-GNSS will be provided - with special consideration of the reliability and quality control of UAV image blocks.

## ZUSAMMENFASSUNG

In diesem Beitrag werden die Komponenten für UAV-Vermessungsprojekte beschrieben und deren Einfluss auf die Qualität der Ergebnisse analysiert. Aus geodätisch-photogrammetrischer Sicht liegt der Fokus auf den Messsensoren (Kamera, Laserscanner, GNSS) sowie den erfassten Messdaten und deren Verarbeitung mittels geeigneter Softwarelösungen. Für Untersuchungen (und ggf. Kalibrierung) der genannten Sensoren sind 3D-Testfelder mit einer entsprechend großen Anzahl signalisierter Passpunkte (GCP) eine geeignete Praxis. Die Testfelder erlauben eine Bewertung der photogrammetrischen Verfahren sowie der beteiligten Komponenten (Sensoren). Gegenwärtig sind bildgebende Sensoren (Kameras) das bevorzugte Messwerkzeug für UAV-Anwendungen, aber auch Laserscanner werden zunehmend auf UAV-Plattformen eingesetzt. Die Leistungsfähigkeit von zwei verschiedenen UAV-Systemen, die häufig in geodätischen Vermessungsprojekten eingesetzt werden, wurde durch entsprechende Testfeldbildflüge untersucht, insbesondere auch durch den Einsatz von RTK-GNSS zur Bestimmung der Sensorpositionen. Abschließend werden Empfehlungen für den kombinierten Einsatz von GCP und präzisem RTK-GNSS gegeben - unter besonderer Berücksichtigung der Zuverlässigkeit und Qualitätskontrolle von UAV-Bildblöcken.

# Aspects of Quality Control for UAV Applications in Photogrammetry

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## 1. INTRODUCTION

In the past decade, the number of users of Unmanned Aerial Vehicles (UAV) in geodetic-photogrammetric applications has increased significantly. Initially, typical tasks were primarily focused on topographic surveying of terrain (including the product "orthophoto") and the volume determination of dumps and pits. To date, projects in the field of cadastre (Rose 2016; Rembold 2022) and engineering surveying (Beckmann 2019) are increasing. This development is accompanied by growing demands on quality and accuracy aspects of the products. The UAV market demonstrates a steady technical development, as well as a continuously increasing number of system providers. The market leader is the Chinese supplier Da-Jiang Innovations Science and Technology Co. Ltd (DJI), although its market share is declining. Technological improvements are the focus of newer systems. These include developments of the UAV hardware, resulting in, for instance, increased flight times, systems for improved integration of the UAV into the airspace, collision detection and avoidance, redundant system components to improve operational safety, and increased navigation quality using multi-frequency GNSS receivers among others.

In regards to the goal of direct georeferencing of imaging and scanning sensors, the availability of RTK/PPK-GNSS technology is of particular importance for geodetic applications, given that it reduces the effort required for local work (ground control point signalisation and determination). Similarly, the successful use of airborne scanners (on UAV) is directly dependent on the quality of the trajectory determination. The use of multi-frequency GNSS receivers offers very good prerequisites for a significantly improved quality of position determination compared to previous possibilities. However, the inertial measurement systems (INS/IMU) installed in UAVs only meet these requirements to a limited extent. Consequently, the measurement of solid angles of the UAV platform remains in need of improvement for the complete determination of the sensor position in space.

Regardless of these features, the most important hardware element of a UAV platform is the used recording sensor. In geodetic-photogrammetric applications, this primarily refers to an imaging sensor, i.e. a digital camera (Przybilla 2017). Recently, however, user interest in the field of UAV-based laser scanners has been growing. The Zenmuse L1 laser scanner, which was made available by DJI in 2021, is aimed at the mass market, particularly due to its price-performance ratio. For this reason, an increase in use - also in surveying projects - can be assumed in the future (Kersten et al. 2022).

## 2. QUALITY ASSURANCE IN UAV APPLICATIONS

Quality assurance activities take place in all areas of data production and service, usually on the basis of national (e.g. DIN – German Industrial Norm) or international (e.g. ISO) standards. However, practice-oriented guidelines (e.g. VDI/VDE - The Association of German Engineers) and/or framework conditions for a process defined by a professionally qualified person/organisation (e.g. fact sheets, DVW 2022) can also be quality-promoting/assuring. In line with this, Neumann & Alkhatib (2019) present applicable specifications in their article "Standards, guidelines and fact sheets for quality assurance in Geodesy". Furthermore, a comprehensive collection of standards on geodesy can be found in the DIN handbook 111 "Geodäsie" (DIN 2022a). Schwieger & Zhang (2019) investigate the subject of quality assurance with a view on "Quality in Engineering Geodesy" and, in particular, the quality features "accuracy and reliability" which are relevant in common geodetic work.

Standards in the field of photogrammetric products (e.g. DIN 18740) and their terminology (DIN 18716) are processed by the committee NA 005-03-02 AA "Photogrammetry and Remote Sensing" (Baltrusch & Reulke 2017; DIN 2022b). While there are already discussions considering a possible normative treatment for quality assurance of UAVs (Neumann & Alkhatib 2019), to date, no corresponding proposals have been elaborated.

## 2.1 Components of the UAV process chain

The following description is an attempt to summarise the process chain and components involved in a surveying project using UAV. To ensure the quality of a successful UAV mission, several interrelated aspects need to be considered as highlighted below: administrative framework, remote pilot/operator, environmental conditions, flight platform/UAV technology, sensors for data acquisition, navigation modules and positioning procedures, as well as expertise and experience (in project operation).

From a geodetic-photogrammetric point of view, the main focus lies on the sensor technology (the actual measuring device) and the associated positioning procedures (e.g. direct georeferencing via RTK-GNSS). In addition, the subsequent numerical procedures for processing the captured image and, if applicable, laser scanning data are of great importance.

### 2.1.1 Administrative framework and proof of competence for remote pilots

The administrative framework for UAV operators has undergone significant reform in recent years. A key objective was to create (as far as possible) equal operating conditions for UAVs within the European Union (EU 2022a, 2022b; LBA 2022). In addition to operator registration and the classification of UAV operations into a category, the proof of competence of remote pilots is an essential element. Importantly, the role of UAVs as participants in the airspace is clearly emphasised by these regulations. Further information can be found, for example, at the Association for Unmanned Aviation (UAV DACH 2022).

### 2.1.2 Environmental conditions

Regardless of administrative requirements, the use of UAVs for measurement purposes is not possible at will. In particular, operational restrictions arise due to weather conditions (e.g. extreme wind conditions), atmospheric disturbances which can influence RTK-GNSS navigation, as well as poor object lighting and visibility conditions, direct influencing the exposure conditions and photographic quality of aerial photographs (e.g. cast shadows, underexposure, image migration, motion blur, etc.) as shown in Fig. 1. Furthermore, flights before and after sunrise (e. g. for taking pictures with thermal cameras) are only possible with official permission.

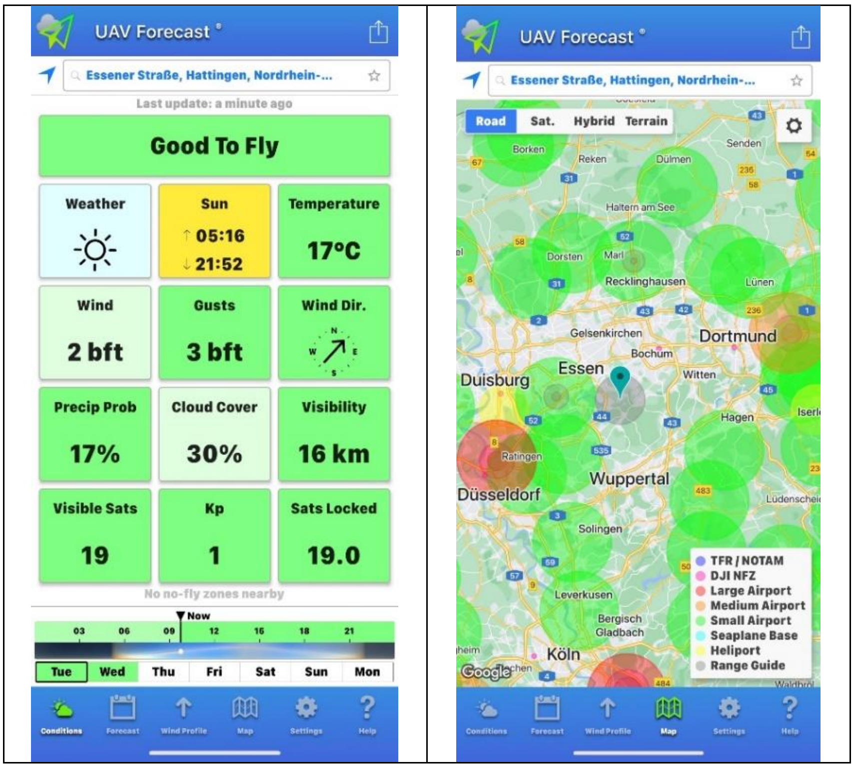

Essener Straße, Hattingen, Nordrhein-...
Last update: a minute ago
Good To Fly
Weather
Sun ↑ 05:16 ↓ 21:52
Temperature 17°C
Wind 2 bft
Gusts 3 bft
Wind Dir.
Precip Prob 17%
Cloud Cover 30%
Visibility 16 km
Visible Sats 19
Kp 1
Sats Locked 19.0
No no-fly zones nearby

Fig. 1: Screenshots of the APP "UAV Forecast" with information on current environmental conditions. Left: weather, right: flight zones (Source: Apple APP Store)

### 2.1.3 Flight platform/ UAV technology

In principle, it can be assumed that the aim of manufacturers is to bring safe UAV systems onto the market. According to European regulation, UAVs for the EU market are equipped with a CE branding. “The CE mark on a product indicates that the manufacturer or importer of that product affirms its compliance with the relevant EU legislation and the product may be sold anywhere in the European Economic Area (EEA). The marking does not indicate EEA manufacture or that the EU or another authority has approved a product as safe or conformant. The EU requirements may include safety, health, and environmental protection.” (Wikipedia 2022) The classification into risk classes (C0-C4) provided in the new European drone regulation includes specifications for the weight and functionality of an UAV (e.g. a system for remote identification that permanently transmits the e-ID, the electronic pilot registration number). In addition, this framework describes instructions for local use (flight altitudes, distance rules) and statements on pilot qualifications (Drone.de 2022). Transitional rules for existing systems, which are currently applied, will end on 1.1.2023. Overall, both technical developments and administrative regulations are positive steps in regards to quality assurance.

### 2.1.4 Sensors for data acquisition

In essence, an UAV can be considered as a multi-sensor system. In principle, this includes basic sensors for stabilising the flight platform, for orientation and positioning in space, for collision avoidance as well as corresponding recording sensors for the targeted recording of selected objects and their properties.

Digital cameras are utilised - with first preference - as geometry-acquiring sensors; this is evenly the case in geodetic applications, although the use of UAV-compatible laser scanners is most likely going to increase in the future. In a market overview, Przybilla (2017) previously highlighted camera systems which are compatible with UAV platforms and classified them into distinct categories.

Over the past five years, developments in camera technology have had their impact on the UAV sector. Larger sensors, occasionally having a significantly higher number of image pixels (e.g. the so-called full-format sensor with an image format of 36 mm × 24 mm), have been made available. At the same time, the enlargement of individual image pixels to 4-5 µm side length has led to an improvement in image quality – most prominently in regards to image noise. Nonetheless, the basic concept of cameras has been retained: they are intended for the mass market of photography, rather than fulfilling the specific requirements of a photogrammetric camera.

In comparison to digital cameras used in classical aerial photogrammetry, the standards for long-term stable metrics are not met by camera systems utilised in the UAV sector. For instance, while the possibility to interchange lenses is increasing the photographic flexibility during recording, it at the same time decreases the desired mechanical stability of the combination of camera body and lens. Moreover, the utility of zoom lenses is a "no-go" from a photogrammetric point of view, given that a reliable determination of the camera constant (which approximately corresponds to the focal length) is not possible. Consequently, a stable metric of the camera can usually not be achieved for photogrammetric applications.

Another camera technique that may influence the geometry of the image is the so-called "rolling shutter" (comparable to a "focal plane shutter"). This describes an image capture method in which an image is not captured as a whole, but line by line, so that the upper part of the image is recorded slightly earlier than the lower part. Importantly, failure to take this effect into account can result in significant degradation of the numerical image orientation resulting from an UAV image flight. However, current software providers have incorporated methodologies for image correction in their programmes (e.g. Vautherin et al. 2016), which (when taken into account by the user) allow this effect to be compensated for. In contrast, the problems caused by the rolling shutter do not occur in cameras with a "global shutter" (central shutter). This essentially corresponds to a strict central perspective, where the complete image is captured simultaneously (Lindstaedt & Kersten 2018).

On the one hand, the quality criteria mentioned above therefore require an individual examination of the geometric and radiometric properties of a camera type (e.g. by university institutions), while on the other hand, their corresponding "treatment" in the photogrammetric evaluation process (by the user), in close context with the topic of a necessary "camera calibration" (see chapter 2.1.6), is crucial.

### 2.1.5 Navigation modules and position determination methods

UAVs are technically equipped with components for autonomous flights. In this regard, knowledge of the spatial position is essential for defining take-off and landing points as well as navigating the UAV to selected destinations. Barometric altimeters, inertial measurement units (IMU) based on micro-electro-mechanical systems (MEMS) and GNSS systems are interlinked here. Most commonly utilised IMUs are capable of measuring spatial angles of 0.1-0.2 gon, which is sufficient to stabilise the flight platform (although it is rather insufficient for measurement variables in frame of direct georeferencing). With positioning accuracies of 3-5 m, 1-frequency GNSS receivers provide adequate quality for performing an image flight, although, this similarly remains is problematic for direct georeferencing of the image data.
For this reason, systems, often referred to as "survey drones" by suppliers, have higher-quality 2-frequency GNSS receivers that can be operated in real-time kinematic (RTK) or post-processing kinematic (PPK) mode. This results in superior positioning accuracies of 1.5-2 cm in attitude and 2-3 cm in altitude with undisturbed GNSS reception. Regardless, atmospheric conditions, as well as the operation of the UAV in urban areas (with visibility dead zones to satellites or limited reception of correction data due to poor mobile phone networks) can influence the quality of the platform and sensor positioning significantly (Przybilla & Bäumker 2020).

### 2.1.6 Expertise and experience (in project operations)

"Practice makes perfect" – this refers to the common sense, in that "one" (m/f/d) can only improve a certain skill through invested time and repetition. In essence, this means that, by building on existing expert knowledge, the work on a variety of projects will increase the experience in handling the measurement system and ultimately result in a substantial improvement of the outcomes. Moreover, by focusing on goal-oriented improvements of the photogrammetric user knowledge through training and education, this will eventually contribute to additional advances in the quality of the overall process in the future.

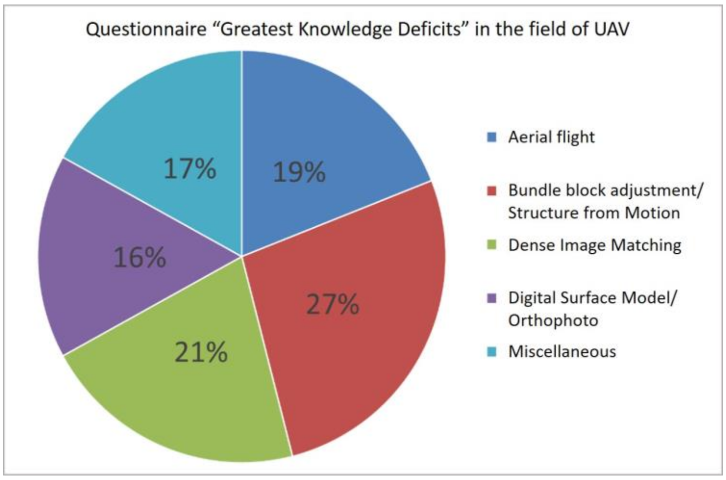


Fig. 2: Survey on "greatest knowledge deficits" in the field of UAVs (sample of 215 votes). (Source: VOXR evaluation within the framework of the DVW seminar UAV 2020)

In line with this, the result of a survey on the "greatest knowledge deficits" in the field of UAV (215 votes) implemented in frame of the DVW UAV Seminar 2020 is highlighted in Fig. 2. Even though such a survey is only representative to a limited extent, the "voting" carried out among an expert audience reveals trends which are aimed in the direction of photogrammetric expertise (bundle block adjustment, dense image matching; 48%), while also referring to the topic complex "point cloud".

## 3. SYSTEM INVESTIGATIONS USING UAV TEST FIELD

The use of test fields has a long tradition in photogrammetry (Ackermann 1975; Ebner et al. 1977; Grün 1986; Grün & Runge 1987). They are an essential element for testing and calibration of digital aerial camera systems in manned aerial photogrammetry (Cramer 2010; Müller & Neumann 2016). Structurally, photogrammetric test fields consist of a group of spatially distributed and signalised points, the latter serving as ground control points (GCP) or check points (CP). Depending on the task, the test field must have a suitable geometric quality, which, for assessments of UAV systems, is in the range of a few millimetres 3D accuracy of the GCP within the geodetic network. To examine the quality of (image-based) point clouds, an extension of the test areas by addition of linear and planar objects provides a valid option. Furthermore, colour panels and bar patterns (e.g. Siemens star) offer the opportunity to derive radiometric and geometric statements about the image and its quality (Meißner 2021).

### 3.1 The Zollern Colliery UAV Test Field

In 2014, an UAV test field was established on the grounds of the Zollern colliery industrial museum in Dortmund by Bochum University of Applied Sciences. This resource was subsequently leveraged in various projects up to the end of 2019 (Nex et al. 2015; Przybilla et al. 2015; Gerke & Przybilla 2016; Cramer et al. 2017; Przybilla et al. 2018; Kersten et al. 2020). Thereby, the zone of the test field, approximately 320 m x 220 m (~7 ha), covers almost the entire area of the colliery. Within the test field, the highest vertical extensions are represented by two approx. 40 m high conveyor frames. Furthermore, it provides up to 49 signalised points arranged in a grid (Fig. 3 left). A detailed description of the geodetic network (regarding configuration, measuring elements, accuracy and reliability) has previously been documented by Bäumker (2020). Since this analysis, various authors have reported the necessity of testing UAV systems using test fields - as well as establishing the required testing facilities (Cramer et al. 2020, Kersten & Lindstaedt 2022).

### 3.2 The Inselpark UAV Test Field in Hamburg-Wilhelmsburg

The Inselpark, located in the district of Wilhelmsburg within Hamburg and host of the International Garden Show in 2013, provides another example of a UAV test field. Created by the Hamburg State Office for Geoinformation and Surveying (LGV), it comprises a total of 45 control points on an area of 150 m × 300 m (Fig. 3 centre). The test area is located at the centre of the park. In comparison to the test field at the Zollern colliery, it has a flat topography without similar high points. The LGV measured a coordinate accuracy of ± 5 mm for the ground control points. A summary of the area is highlighted in Figure 3 (centre), depicting the uniform distribution of the GCP over the approx. 4.5 ha area of the Inselpark. Before each flight campaign, all GCP are signalised using boards made of waterproof plastic (50 cm × 50 cm) (Fig. 3 right). Overall, the test site has already been utilised in several campaigns implemented by the LGV and in cooperation with the HCU Hamburg (Kersten & Lindstaedt 2022; Kersten et al. 2022).

Fig. 3: GCP overview for UAV test field Zollern colliery (left, Source: Bäumker 2020) - and UAV test field Inselpark Hamburg-Wilhelmsburg (centre), and GCP targets on different surfaces (right) - grass, asphalt, sand and stone (Kersten et al. 2022)

### 3.3 Remarks on the photogrammetric process

In UAV applications, the photogrammetric process is closely related to the terms Structure from Motion (SfM), image triangulation (bundle block adjustment, BBA) and Dense Image Matching (DIM). Corresponding functionalities are made available via software packages such as Agisoft Metashape, Pix4Dmapper and others. The workflows offer the unique possibility for the user to implement projects without having in-depth photogrammetric expertise. This is particularly useful, given that the interactions of different elements in the photogrammetric imaging process of the central perspective are quite complex. Within the framework of the bundle block adjustment, the collinearity condition (object point, projection centre and image point lie on a straight line) is carried out numerically. For this, information about the camera (interior orientation - IOR), its positions in space (exterior orientation - EOR), and the definition of a geodetic datum through ground control points, are utilised. Ultimately, this process aims to determine additional 3D points (point clouds). However, in regards to quality assurance, the result should have undergo (project-dependent) accuracy and reliability checks.

### 3.4 Objectives of the investigations

The following investigations in the two UAV test fields focus on possible influences of camera sensors, the direct determination of image positions with RTK-GNSS and the use of ground control points for the georeferencing of image blocks (Fig. 4).

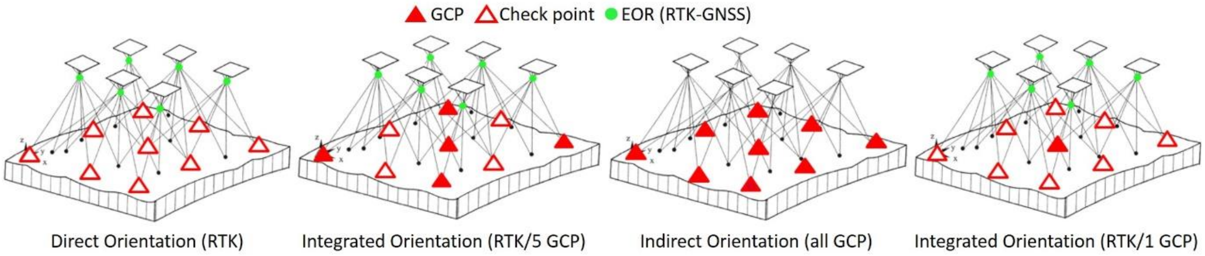


Fig. 4: Variants of aerial image block orientation (georeferencing)

### 3.4.1 Phantom 4 RTK (with Zenmuse X4S)

The assessments described in this chapter have previously been published in Przybilla & Bäumker (2020), with the main results being summarised in the following. In particular, the results from test runs of two identical Phantom 4 RTK, equipped with the integrated camera Zenmuse X4S (20 MPixel) and carried out at the Zollern colliery test field, are shown in Figs. 5 and 6. Here, the image orientations were conducted with common configurations consisting of a combination of GCP and exterior orientation measured by RTK-GNSS (integrated sensor orientation). For all settings, a uniform interior orientation (UNIFIED) was introduced for the two partial flights of a cross-flight. Additionally, another calculation was implemented relying on two separate interior orientations (SEPARATE) for the block, georeferencing with observed EOR and 4 GCP in the block corners (optional: plus one GCP in the centre of the image block). Using this alternative approach, the major aim was the detection of possible influences of changing focuses of the camera.

The check of block geometry, block deformations in particular, is performed using the root mean square errors (RMSE) at check points (CP). Thereby, the influence of georeferencing types on the respective block becomes apparent. The following effects can be determined:

a) Direct orientation using measured EOR (RTK-GNSS): The deviations at the CP, related to the position coordinates, are within the range of the RTK accuracy (10-20 mm). However, significantly large deviations in height are found occasionally. A reliable referencing for this variant (without GCP) is not recognisable.
b) Indirect orientation with maximum number of GCP: Since all GCP are utilised for georeferencing, a control based on independent CP is not possible in this scenario. Notably, this georeferencing variant is associated with a very high terrestrial effort.
c) Indirect orientation with minimum number of GCP: Based on the results for georeferencing using 4 GCP in the block corners, it becomes evident that sufficient stability cannot be achieved in the image block. While the positional deviations of the CP are still within the range of the GSD, the height deviations exceed it by a factor of 15 - 30. A possible explanation for this result could either be found in the camera metrics or the apparent and insufficient possibilities for simultaneous camera calibration.
d) Integrated orientation using measured EOR (RTK-GNSS) and four GCP: The results demonstrate the effectiveness of the integrated georeferencing based on the RTK-GNSS measurements in combination with GCP in the block corners. Overall, the deviations at the CP are in range of the GSD, in some occurrences even below.

e) Integrated orientation using measured EOR (RTK-GNSS) and one GCP: Although the direct georeferencing with measured exterior orientation is characterised by significant height deviations in the available data sets, the positive effects of an additional control point (in the centre of the block) becomes clearly evident. Consequently, the systematic height deviations at the CP are reduced to approx. 15 - 30 mm and are thus at accuracy levels of the RTK-GNSS measurements. Moreover, the image orientation accuracy achieved is sufficient for topographic applications.


RMSE CP - Phantom 4 RTK System A

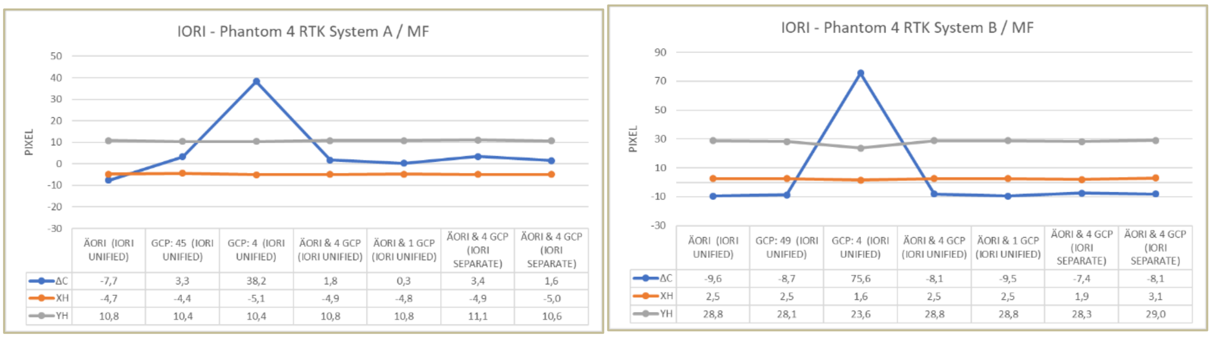
RMSE CP - Phantom 4 RTK System B

|  | ÄORI | 45 GCP (IORI UNIFIED) | 4 GCP (IORI UNIFIED) | ÄORI & 4 GCP (IORI UNIFIED) | ÄORI & 1 GCP (IORI UNIFIED) | ÄORI & 4 GCP (IORI SEPARATE) |
|---|---|---|---|---|---|---|
| ■ X-Error | 11,3 | - | 14,3 | 11,7 | 11,3 | 11,4 |
| ■ Y-Error | 9,8 | - | 10,5 | 9,2 | 10,0 | 8,7 |
| ■ Z-Error | 145,9 | - | 243,3 | 12,3 | 29,8 | 9,6 |
| ■ 3D-Error | 146,7 | - | 244,0 | 19,3 | 33,4 | 17,2 |

|  | ÄORI | 49 GCP (IORI UNIFIED) | 4 GCP (IORI UNIFIED) | ÄORI & 4 GCP (IORI UNIFIED) | ÄORI & 1 GCP (IORI UNIFIED) | ÄORI & 4 GCP (IORI SEPARATE) |
|---|---|---|---|---|---|---|
| ■ X-Error | 6,1 | - | 13,0 | 5,5 | 6,2 | 5,5 |
| ■ Y-Error | 8,6 | - | 16,9 | 8,3 | 8,6 | 8,4 |
| ■ Z-Error | 15,6 | - | 445,7 | 14,2 | 15,0 | 17,5 |
| ■ 3D-Error | 18,8 | - | 446,2 | 17,3 | 18,4 | 20,2 |

Fig. 5: RMSE values at the check points (CP) depending on the type of georeferencing (direct: EOR - indirect: GCP - integrated: EOR+GCP) (Systems A and B)

To perform in-situ calibration of a camera in the BBA an essential prerequisite, in addition to a suitable image block configuration (here: cross-flight), is the availability of corresponding georeferencing information (GCP, measured elements of the EOR). In line with this, Fig. 6 depicts changes in the parameters camera constant (Δc) and principal point ($x_H$, $y_H$) depending on the block referencing. Remarkably, only small changes in the principal point (< 1 pixel) are observable, arguing for the high stability of the respective camera.


IORI - Phantom 4 RTK System A / MF

IORI - Phantom 4 RTK System B / MF

|  | ÄORI (IORI UNIFIED) | GCP: 45 (IORI UNIFIED) | GCP: 4 (IORI UNIFIED) | ÄORI & 4 GCP (IORI UNIFIED) | ÄORI & 1 GCP (IORI UNIFIED) | ÄORI & 4 GCP (IORI SEPARATE) | ÄORI & 4 GCP (IORI SEPARATE) |
|---|---|---|---|---|---|---|---|
| ΔC | -7,7 | 3,3 | 38,2 | 1,8 | 0,3 | 3,4 | 1,6 |
| XH | -4,7 | -4,4 | -5,1 | -4,9 | -4,8 | -4,9 | -5,0 |
| YH | 10,8 | 10,4 | 10,4 | 10,8 | 10,8 | 11,1 | 10,6 |

|  | ÄORI (IORI UNIFIED) | GCP: 49 (IORI UNIFIED) | GCP: 4 (IORI UNIFIED) | ÄORI & 4 GCP (IORI UNIFIED) | ÄORI & 1 GCP (IORI UNIFIED) | ÄORI & 4 GCP (IORI SEPARATE) | ÄORI & 4 GCP (IORI SEPARATE) |
|---|---|---|---|---|---|---|---|
| ΔC | -9,6 | -8,7 | 75,6 | -8,1 | -9,5 | -7,4 | -8,1 |
| XH | 2,5 | 2,5 | 1,6 | 2,5 | 2,5 | 1,9 | 3,1 |
| YH | 28,8 | 28,1 | 23,6 | 28,8 | 28,8 | 28,3 | 29,0 |

Fig. 6: Changes in the parameters of the interior orientation (Δc, $x_H$, $y_H$) as a function of the block referencing as well as common or separate parameters for the partial flights (systems A and B). (Note: the deviations Δc refer to a uniform starting value)

In addition, the influences of block georeferencing on the parameter "camera constant" becomes evident. When only four ground control points in the block corners are utilised, a reliable determination of this parameter becomes impossible. In contrast to all other variants, the deviations increase to 20 - 80 pixels. The corresponding (negative) consequences are shown in Fig. 5, particularly emphasised by the height deviations at the GCP.

In summary, both, common (UNIFIED) or separate (SEPARATE) parameterisation of the interior orientation for partial flights, highlight almost identical results for the RMSE values at the GCP (Fig. 5) and for the variation of the camera constant respectively (Fig. 6). Hence, stability of the investigated parameters during the course of two partial flights of the cross formation can be assumed.

### 3.4.2 Matrice 300 RTK with Zenmuse P1

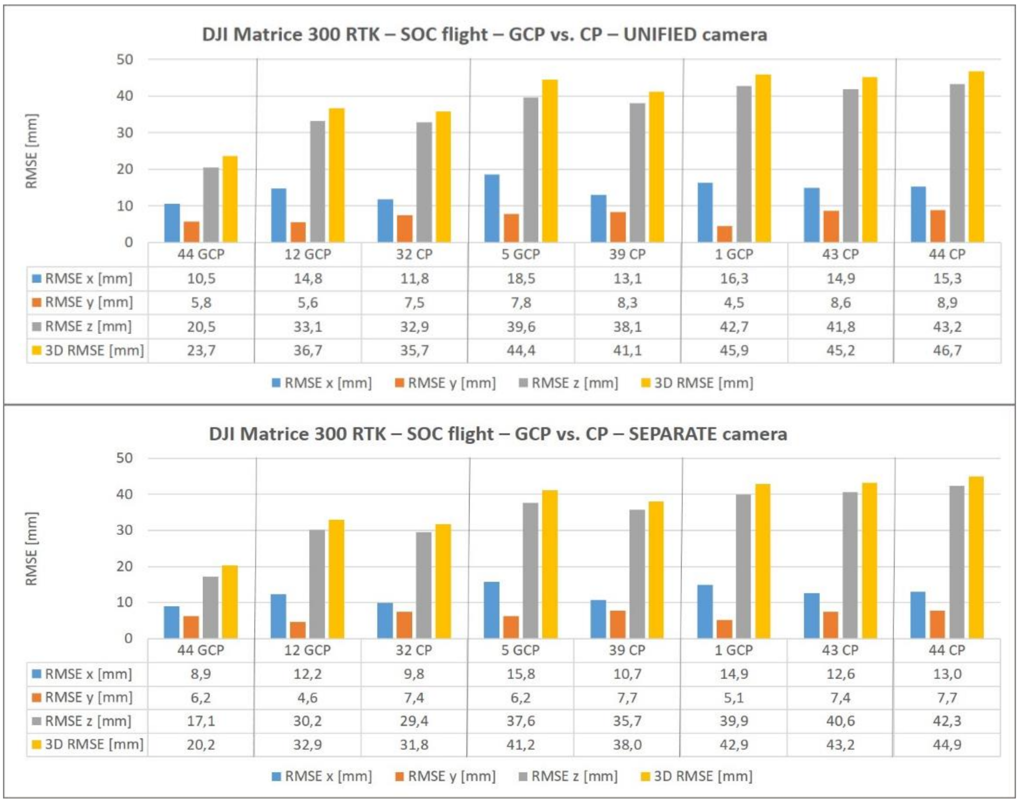
The Matrice 300 RTK, one of the latest UAV from DJI, is in part designed for geodetic-photogrammetric users as a target group. It is equipped with a Zenmuse P1(DJI 2022), a full-format digital camera which can be utilised with three different interchangeable lenses (24 mm, 35 mm, 50 mm). However, the flexibility of the lens selection comes at the price of possible mechanical instabilities (mechanical clearance between the camera body and the optics), a feature highly desired for photogrammetric applications.

The following results are based on an image flight using the Zenmuse P1 (35 mm lens) in the Hamburg test field. In this scenario, the capture mode referred to by DJI as "Smart Oblique Capture" (SOC) was used. In addition to nadir images, up to four additional oblique images were acquired per capture location, depending on the UAV's position in the image block. In regards to the block geometry, this means a significant increase in the number of ray intersections, with a simultaneous improvement in the geometry. Importantly, an image set acquired following this procedure (flight altitude above ground: 70 m, longitudinal and transverse coverage: 80%, number of images: 2215, including 441 nadir images, GSD nadir: 8.8 mm, GSD oblique: 10.2 mm) should have a high level of accuracy, especially in respect to the expected height accuracy.

Following this, Fig. 7 highlights the results (RMSE values) from different calculation variants. The block georeferencing was implemented utilising the image positions measured by RTK-GNSS (EOR) in conjunction with varying GCP configurations. Strinkingly, the results show poor height accuracy of the highly redundant image block; even with the maximum number of GCP (44), the GSD is approximately 2-fold higher. Moreover, variants with a lower number of GCP further decrease the height accuracy significantly (factor 4 of the GSD). Notably, this also applies to the block that is georeferenced exclusively on the basis of the RTK observations (Fig. 7, right column).

In general, georeferencing of the image block through direct georeferencing does not appear to be recommendable. Regardless, even the integrated georeferencing (here: 5 GCP + RTK) is noticeably worse in contrast to the results from the Phantom 4 RTK (4 GCP + RTK, see chapter 3.4.1).

In essence, systematic effects which result from the configuration between the RTK-GNSS system (antenna centre) and the projection centre of the camera are to be expected. This so-called "lever arm" is calculated depending on the spatial position (of the camera) and applied as a correction variable to the RTK-GNSS position measured in each case. In principle, time synchronisation errors, resulting from camera shutter release and registration of the image position by RTK-GNSS, would also be conceivable for the SOC flight mode.



|  | 44 GCP | 12 GCP | 32 CP | 5 GCP | 39 CP | 1 GCP | 43 CP | 44 CP |
|---|---|---|---|---|---|---|---|---|
| RMSE x [mm] | 10,5 | 14,8 | 11,8 | 18,5 | 13,1 | 16,3 | 14,9 | 15,3 |
| RMSE y [mm] | 5,8 | 5,6 | 7,5 | 7,8 | 8,3 | 4,5 | 8,6 | 8,9 |
| RMSE z [mm] | 20,5 | 33,1 | 32,9 | 39,6 | 38,1 | 42,7 | 41,8 | 43,2 |
| 3D RMSE [mm] | 23,7 | 36,7 | 35,7 | 44,4 | 41,1 | 45,9 | 45,2 | 46,7 |

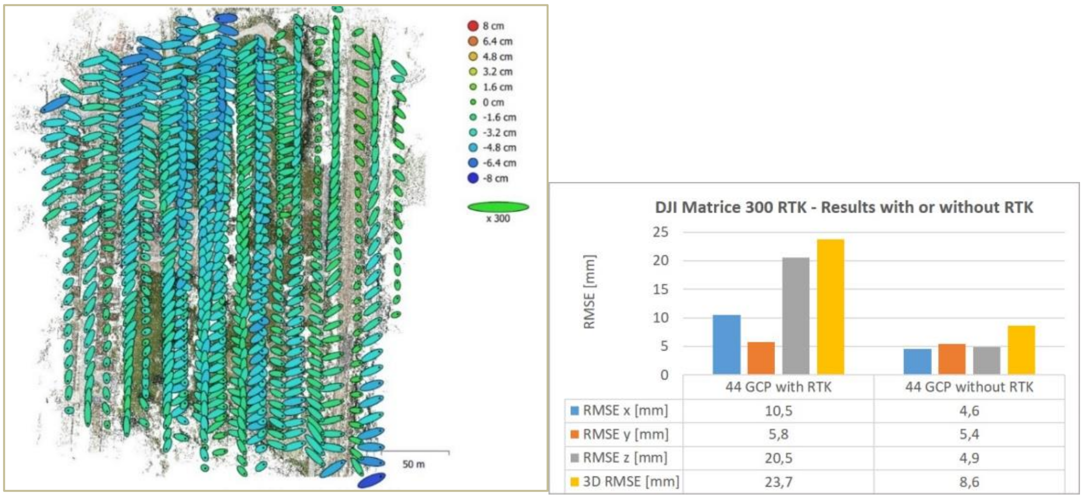
|  | 44 GCP | 12 GCP | 32 CP | 5 GCP | 39 CP | 1 GCP | 43 CP | 44 CP |
|---|---|---|---|---|---|---|---|---|
| RMSE x [mm] | 8,9 | 12,2 | 9,8 | 15,8 | 10,7 | 14,9 | 12,6 | 13,0 |
| RMSE y [mm] | 6,2 | 4,6 | 7,4 | 6,2 | 7,7 | 5,1 | 7,4 | 7,7 |
| RMSE z [mm] | 17,1 | 30,2 | 29,4 | 37,6 | 35,7 | 39,9 | 40,6 | 42,3 |
| 3D RMSE [mm] | 20,2 | 32,9 | 31,8 | 41,2 | 38,0 | 42,9 | 43,2 | 44,9 |

Fig. 7: RMSE values at the ground control (GCP) and check points (CP) depending on the georeferencing type for the "Smart Oblique Capture" (SOC) image flight of the Matrice 300 RTK (Top: One IOR for all images of the flight. Bottom: Three different IORs, separated into nadir and oblique images)

The effects highlighted above can be assessed by using an indirect georeferencing of the block with all available GCP, while simultaneous "switching off" the RTK observations in the BBA. Fig. 8 (left) clearly demonstrates systematic corrections of the RTK positions (EOR), both in the orientation or shape of the error ellipses (position) and in height (error in Z represented by the colour of the ellipses). Here, the estimated camera positions are highlighted by a black dot. At the same time, the RMSE values at the GCP decrease significantly (Fig. 8 right) to an accuracy level which is equal to the expected values. However, the above-mentioned possible causes for this problem need to be verified by follow-up studies and additional investigations.

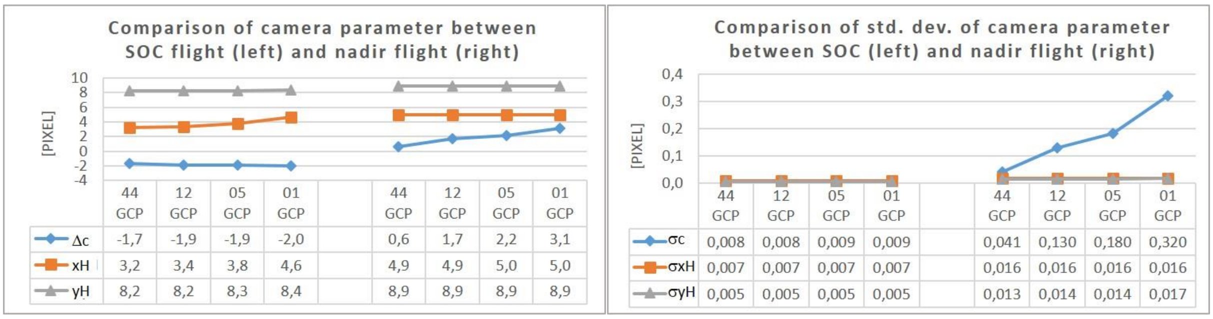
An important aspect for the accuracy and reliability of photogrammetric point determination by UAV image flight data is represented by the camera calibration, given that the user cannot constantly assume a stable interior orientation of the camera. This poses the question, which imaging configuration offers the best conditions for a significant estimation of the camera parameters?

Recently, Przybilla (2020) and Kersten et al. (2020) showed that a cross-flight with 20% different flight altitudes guarantees good conditions for camera calibration, especially if the test field or the object space has neglectable differences in ground height. In line with this, during the assessments of the Matrice 300 RTK in the Hamburg test field, it could be proven that a "Smart Oblique Capture" image flight as a combination of nadir and oblique images provides a significantly better foundation for a camera calibration than a pure nadir image flight.



| | 44 GCP with RTK | 44 GCP without RTK |
|---|---|---|
| ■ RMSE x [mm] | 10,5 | 4,6 |
| ■ RMSE y [mm] | 5,8 | 5,4 |
| ■ RMSE z [mm] | 20,5 | 4,9 |
| ■ 3D RMSE [mm] | 23,7 | 8,6 |

Fig. 8: "Smart Oblique Capture" image flight of the Matrice 300 RTK: Camera positions and residuals (ERROR) from Agisoft Metashape (left). RMSE values of 44 GCP with RTK-GNSS (left) and without RTK-GNSS (right)



| | 44 GCP | 12 GCP | 05 GCP | 01 GCP | | 44 GCP | 12 GCP | 05 GCP | 01 GCP |
|---|---|---|---|---|---|---|---|---|---|
| Δc | -1,7 | -1,9 | -1,9 | -2,0 | | 0,6 | 1,7 | 2,2 | 3,1 |
| xH | 3,2 | 3,4 | 3,8 | 4,6 | | 4,9 | 4,9 | 5,0 | 5,0 |
| yH | 8,2 | 8,2 | 8,3 | 8,4 | | 8,9 | 8,9 | 8,9 | 8,9 |

| | 44 GCP | 12 GCP | 05 GCP | 01 GCP | | 44 GCP | 12 GCP | 05 GCP | 01 GCP |
|---|---|---|---|---|---|---|---|---|---|
| σc | 0,008 | 0,008 | 0,009 | 0,009 | | 0,041 | 0,130 | 0,180 | 0,320 |
| σxH | 0,007 | 0,007 | 0,007 | 0,007 | | 0,016 | 0,016 | 0,016 | 0,016 |
| σyH | 0,005 | 0,005 | 0,005 | 0,005 | | 0,013 | 0,014 | 0,014 | 0,017 |

Fig. 9: Comparison of camera parameters (left) and their standard deviations (right) for the "Smart Oblique Capture" image flight and the nadir image flight of the Matrice 300 RTK (note: the deviations Δc refer to an average value)

Following this, Fig. 9 represents a comparison of the estimated camera parameters (left) and their standard deviations (right) for the "Smart Oblique Capture" image flight as well as a separate nadir image flight. Due to the high redundancy, the camera constant (Δc) varies by only 0.3 pixels for the SOC image flight, whereas Δc changes by 2.5 pixels between the distinct GCP variants for the nadir flight. However, the principle point ($x_H$, $y_H$) remains remarkably stable for both image blocks, although there was one exception. Furthermore, the three camera parameters had a significantly lower standard deviation in the SOC image flight (Fig. 9 right) than in the nadir image flight, suggesting a more stable camera calibration. Lastly, in the nadir image flight, the standard deviation for the camera constant was 36x higher, which could also be attributed to the flat profile of the test field.

## 4. CONCLUSIONS & OUTLOOK

The choice of components utilised in UAV-based surveying projects is critical for its successful outcome. To facilitate these decisions, this article not only highlights various features which need to be taken into account for a surveying project using UAVs, but also demonstrates analyses of their influence on the quality of results. In the light of geodetic and photogrammetric applications, the measuring sensors (camera, laser scanner, GNSS), the resulting measurement data and their processing using appropriate software solutions is of highest importance.

Moreover, spatial test fields with a correspondingly large number of signalised ground control points provide appropriate foundations for testing (and, if necessary, calibrating) of the aforementioned systems. Importantly, they simultaneously enable an evaluation of the processes itself as well as the components involved. Notably, while imaging sensors are the preferred option for UAV-based measurements, laser scanners are receiving increased popularity (Studnicka et al. 2020; Kersten et al. 2022; Mandlburger 2022).

Here, two UAV systems, which are frequently in use for geodetic test practice, were assessed for their performance within test field flights, in particular in combination with the "RTK-GNSS" process component.

For the DJI UAV system, consisting of the Matrice 300 RTK platform and the Zenmuse P1 camera, "anomalies" were detected during the test, potentially resulting from the manufacturer's description of the geometry between the antenna centre and the projection centre of the camera (lever arm). Further investigations are necessary to further unravel the origin of this problem.

The combination of precise (±2-3 cm) and reliable RTK-GNSS measurements and highly accurate signalised ground control points (±5 mm) within a spatial test field, enabled the determination of the interior and exterior orientation parameters as well as a stabilisation of the aerial image block by bundle block adjustment. In the context of a cross-flight, the acquisition at different flight altitudes increased the block accuracy, combined with the effect of an improved calibration of the camera constant.

Moreover, a UAV flight should not be implemented completely independent of GCP. Taking into account the potential accuracy of the used UAV system as well as the basic geodetic principles, e.g. ensuring the reliability of a measurement, GCP cannot be neglected. However, for topographic applications with lower accuracy specifications, one ground control point in the centre of object space could possibly be sufficient, if the RTK-GNSS measurements are reliably available at a standard deviation of ±2-3 cm. Overall, it is still recommended to distribute at least four to five GCP in the object space to control successful UAV flights.

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