Assessment of UAV image quality in terms of optical resolution

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ABSTRACT: The aim of this study was to assess the quality of images from different UAV sensors in terms of their optical resolution, expressed by the MTF10 parameter. The study was conducted for four cameras: Mavic 3E, Matrice 4E, Phantom 4 RTK and Zenmuse P1, under different weather and lighting conditions, with varying flight altitudes and ISO settings. The Siemens Star pattern and ResolvingPower software provided by The German Aerospace Center (DLR) were used in the analysis. The results showed a significant effect of flight altitude, time of day and ISO sensitivity on image quality. A decrease in sharpness (MTF10) was observed with increasing distance from the image centre and at higher ISO values. The conclusions of the study may be helpful in planning photogrammetric missions using UAVs, enabling better-quality image data.

KEY WORDS: optical resolution, image quality, UAV, GSD, GRD

1. INTRODUCTION

Images acquired from unmanned aerial vehicles (UAVs) have successfully become part of modern photogrammetry and remote sensing. However, the quality of the images taken by the UAV cameras raises many questions, similar to the increasingly widespread use of RGB matrices in aerial photogrammetry (Meißner et al., 2017). This topic has been reflected in scientific and industrial research (Meißner et al., 2019; Schulz et al., 2021), resulting in the introduction of a measure of ground-resolved optical resolution - GRD (Ground Resolved Distance) of the image beside a measure of geometric resolution - GSD (Ground Sampling Distance).

UAV images are acquired with sensors of varying quality and often in much more varied lighting conditions than is the case with aerial imagery. In addition, an increase in sensor sensitivity (ISO value) is generally used to compensate for poor light conditions, which has a negative impact on image quality. The main indicators of image quality are the signal-to-noise ratio and the radiometric accuracy and stability of the sensor. Assessment of radiometric image quality, which is influenced by sensor features defined by sharpness, contrast, and resolution, enables the objective assessment of the potential of such data (Kedzierski & Wierzbicki, 2015). These features determine the MTF (Modulation Transfer Function) function, which is the response of the optical system, depending on the spatial frequency. The MTF of an imaging system is a measure of the resolution (image sharpness, visibility of detail) the system can achieve (Meißner et al., 2018). Recent research highlights the limitations of relying solely on GSD when evaluating the spatial resolution of UAV imagery. Studies (Lim et al., 2018) show that GRD and image sharpness vary with altitude and environmental conditions, suggesting that, for example, edge analysis can help identify optimal flight parameters for specific UAV sensor configurations.

The aim of the research and experiments was to assess the actual quality of these images and to demonstrate how photogrammetric flights should be designed to maintain imaging quality and how much this depends on the drone used.

2. METHODOLOGY

The study was conducted using UAV images from four different sensors. Flight campaigns were conducted in different seasons, in various lighting and weather conditions, and at different altitudes. The main objective was to determine the optical resolution of UAV cameras as a function of varying mission parameters. The methodology assumes the analysis of image data and evaluation of the optical resolution using the software ResolvingPower developed by The German Aerospace Center (DLR).

Spatial resolution determination was done with the Siemens Star target as the most suitable test pattern for UAV sensors (Orych, 2015). Measurement includes several confidences (centre accuracy, interpolation method, overall distribution).

2.1 Description of the test area and data

The analysis was conducted for 4 different cameras on the UAVs: Mavic 3 Enterprise, Matrice 4 Enterprise, Phantom 4 RTK and Matrice 300 RTK with P1 Camera. The parameters of the cameras are presented in Table 1.

Camera	Mavic 3E	Matrice 4E	Phantom 4 RTK	Zenmuse P1
Pixel size	3.3 μm	3.3 μm	2.4 μm	4.4 μm
Focal length	12.29 mm	12.29 mm	8.8 mm	35 mm
FOV	84°	84°	84°	63.3°
Resolution	5280×3956		5472×3648	8192×5460
Shutter type	Mechanical shutter			

Table 1. Parameters of the cameras used in the experiment

The cameras' tests with Siemens star were conducted over the test field for UAVs in Józefosław near Warsaw. The images were taken so that the Siemens star was in different parts of the image frame. Additionally, different flight altitudes above ground level (AGL), i.e. photographing distance and ISO settings, were taken into account.

2.2 Scheme of experiments

As part of the research, a number of experiments were performed. The research was divided into two main experimental stages. The first tests were aimed at verifying the effect of flight height on the optical resolution of the image, determined by the MTF10 index. An example demonstrating differences in the appearance of the Siemens star in images taken from different heights is shown below (
Figure 1). Images from the DJI Zenmuse P1 camera were taken from heights of 40 m, 60 m, and 80 m, corresponding to GSD: 0.50 cm, 0.75 cm and 1 cm, respectively. They were acquired at the same time of day but with varying ISO values.

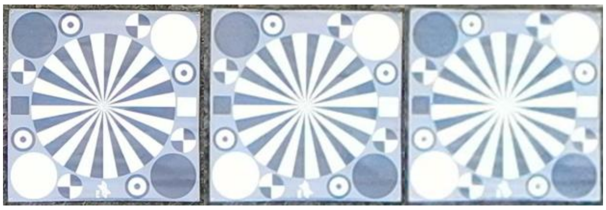

Figure 1. Example of Siemens star on images from P1 camera (40, 60 and 80 m AGL).

For the Mavic 3E and Matrice 4E, images were also captured at different altitudes, but at constant ISO values and under similar lighting conditions. Images from the Mavic 3E were taken from heights of 11 m, 18 m, 24 m, 33 m, 39 m, 47 m, 60 m, corresponding to GSD: 0.29 cm, 0.38 cm, 0.52 cm, 0.88 cm, 1 cm, 1.25 cm, 1.60 cm, respectively. Images from the Matrice 4E were taken from heights of 10 m, 20 m, 40 m, 60 m, 80 m, 90m, corresponding to GSD: 0.27 cm, 0.54 cm, 0.81 cm, 1.08 cm, 1.62 cm, 2.42 cm, respectively.

For the Phantom 4 RTK drone, variable altitudes were similarly assumed, but in addition, the images were taken under different lighting conditions (more than an hour difference in the time the images were taken). The ISO remained constant at 800, hence it was possible to analyse the effects of lighting and flight height. Three flight heights were used in the experiment: 36 m, 55 m, and 91 m, corresponding successively to GSD values of 1.00 cm, 1.50 cm, and 2.50 cm.

The second stage focused on the effects of data acquisition time, daylight intensity and ISO sensitivity on imaging quality. This research aimed to assess the impact of exposure conditions (varying ISO, different shooting times) and the position of the test pattern relative to the centre of the frame on the MTF10 value. In this part of the research, a series of flights were carried out for DJI Mavic 3E, Phantom 4 RTK and Matrice 300 RTK with a P1 camera at a fixed flight altitude corresponding to GSD = 1 cm. Data were acquired in November, when there are significant differences in daylight intensity during the afternoon. For images taken between 1 p.m. and 3 p.m., a substantial decrease in light brightness is observed, which had a direct impact on the need to increase the ISO value and consequently on image quality and noise levels.

In addition to the evaluation of image quality parameters, the second stage of the experiment involved the analysis of point clouds generated from dense image matching. The aim was to determine the precision of the mapping of the geometry of the objects. Two objects (concrete columns) with known, accurately measured coordinates were selected for the analysis, which allowed well-defined planes to be generated. From the measurements, reference planes were determined for each object, from which the distances of the cloud points acquired from each mission were then calculated.

3. RESULTS

3.1 Influence of flight altitude on optical resolution

The following tests were designed to assess the effect of flight altitude on the optical resolution of the images, represented by MTF10 values.

3.1.1 DJI Zenmuse P1

Below is a chart of the distribution of MTF10 values for the P1 camera as a function of altitude (Figure 2). As the altitude increases, the MTF10 values for each of the R, G and B bands decrease, confirming a deterioration in image quality (less sharpness). The change in ISO is also noticeable and increases with the height, suggesting that the system might have been automatically compensating for lower exposures while increasing noise. This had the effect of degrading the optical quality of the image.

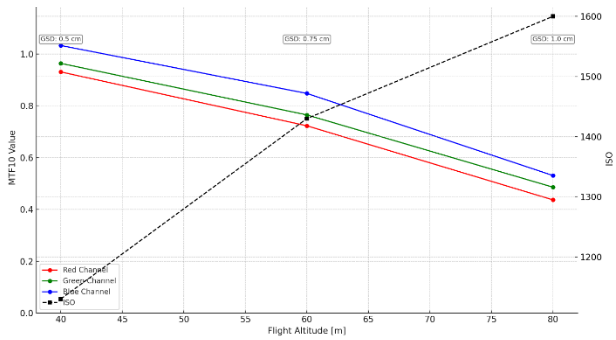

Figure 2. Dependence of MTF10 value on flight altitude and ISO parameter for DJI Zenmuse P1.

3.1.2 Mavic 3E and Matrice 4E

For the Mavic 3E (ISO 100), the MTF10 values gradually decrease in the individual R, G and B bands as altitude decreases (Figure 3). In contrast, for the Matrice 4E drone (ISO 120), MTF10 values remain consistently high, often exceeding a value of 1. This may suggest that some additional sharpening filter has been applied to the images by the camera on-board image processor, especially as all three RGB channels show similar trends.

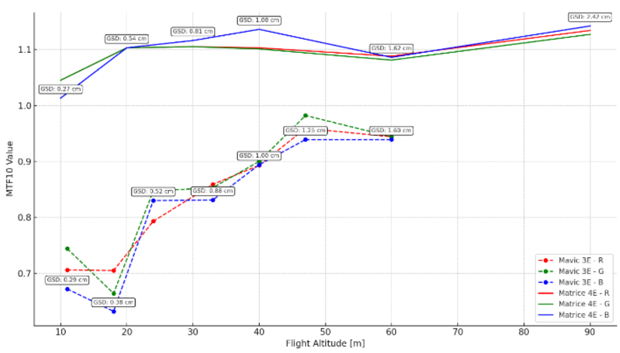

Figure 3. The values of MTF10 for Mavic 3E and Matrice 4E in relation to the flight altitudes.

3.1.3 Phantom 4 RTK

As can be seen (Figure 4), the time of acquisition and the lighting conditions were essential factors. The marked difference between the images captured at different times may suggest that the images taken earlier were overexposed, which negatively affected the sharpness of the image. It can be said that the influence of lighting conditions prevails over the influence of GSD.

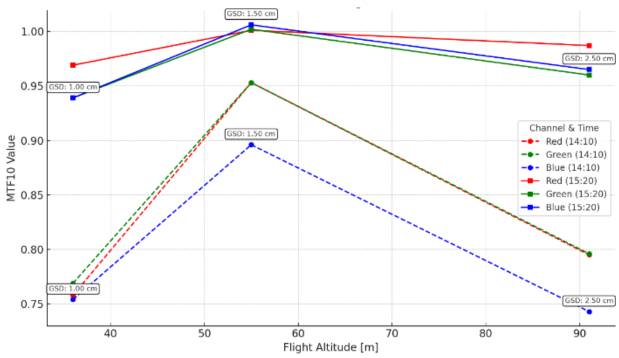

Figure 4. The values of MTF10 for Phantom 4 RTK in relation to the flight height for images acquired at different times.

Camera	Flight Height	MTF10 (AVG)	GRD	GSD [cm]	ISO	Time
DJI Zenmuse P1	40m	0,976	0,51	0,50	1130	03:30 p.m.
DJI Zenmuse P1	60m	0,779	0,96	0,75	1430	03:30 p.m.
DJI Zenmuse P1	80m	0,485	2,06	1,00	1600	03:30 p.m.
P4_RTK	36m	0,760	1,31	1,00	800	02:10 p.m.
P4_RTK	36m	0,949	1,05	1,00	800	03:20 p.m.
P4_RTK	55m	0,934	1,61	1,50	800	02:10 p.m.
P4_RTK	55m	1,003	1,50	1,50	800	03:20 p.m.
P4_RTK	91m	0,778	3,21	2,50	800	02:10 p.m.
P4_RTK	91m	0,971	2,58	2,50	800	03:20 p.m.
M3E	60m	0,944	1,70	1,60	100	11:30 a.m.
M3E	47m	0,959	1,30	1,25	100	11:30 a.m.
M3E	39m	0,897	1,17	1,05	100	11:30 a.m.
M3E	33m	0,859	1,02	0,88	100	11:30 a.m.
M3E	24m	0,806	0,79	0,64	100	11:30 a.m.
M3E	18m	0,667	0,72	0,48	100	11:30 a.m.
M3E	11m	0,706	0,41	0,29	100	11:30 a.m.
Matrice4	90m	1,134	2,14	2,42	120	9 a.m.
Matrice4	80m	1,078	2,00	2,15	120	9 a.m.
Matrice4	60m	1,112	1,45	1,61	120	9 a.m.
Matrice4	40m	1,105	0,97	1,07	120	9 a.m.
Matrice4	20m	1,098	0,49	0,54	120	9 a.m.
Matrice4	10m	1,034	0,26	0,27	120	9 a.m.

Table 2. A summary of the parameters of the images taken for four sensors: DJI Zenmuse P1, Phantom 4 RTK, Mavic 3 Enterprise and Matrice 4 Enterprise. The table includes altitude of flight (AGL), GSD, ISO, time the image was taken and average MTF10 (average for the three channels) and GRD values.

The results summarised in Table 2 further demonstrate the relationship between GSD (Ground Sampling Distance) and the optical resolution GRD (Ground Resolved Distance). Under ideal conditions, the GRD should be equal to or very close to the GSD, meaning that the imaging system is using its full geometric potential. In practice, however, numerous factors influence this, mainly the quality of the optical system, but also the flight altitude, lighting conditions, and ISO, analysed in the study.

For most cases, the GRD is greater than the GSD, indicating a deterioration in optical resolution relative to field pixel size - the image represents detail less effectively. In general, it can be seen that the higher the flight altitude, the greater the discrepancy between GRD and GSD. The best agreement between GRD and GSD was observed at low flight altitude and low ISO. From these results, it can be seen that the best result at different altitudes was shown by the camera in the Mavic 3E drone and performed most favourably in terms of consistency of imaging quality.

As mentioned in the methodology section, taking into account the abovementioned results, additional, more extensive experiments were carried out, where the influence of the hour of flight (daylight influence) was investigated. In addition, the tests carried out took into account the position distance of the Siemens star from the centre of the image.

3.2 Extended experiments - influence of lighting conditions

3.2.1 Mavic 3E

For the Mavic 3E, flights were performed at an altitude of 38 m, for which the GSD was 1 cm. Two flights were performed for the same area. The first was taken at 13:30 at an ISO of 400, the second over an hour later at an ISO of 800. For each of them, 10 images were selected in which the Siemens star was mapped in different parts of the image frame.

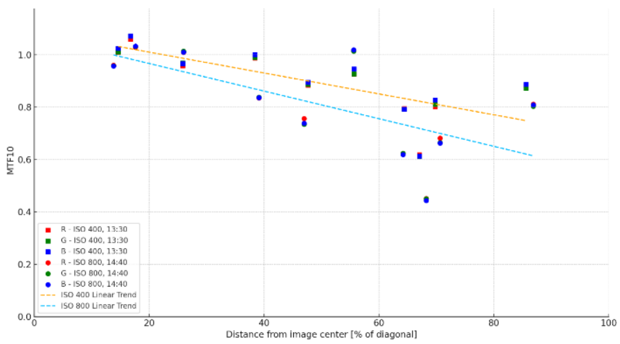

Figure 5. The values of MTF10 in relation to the distance from the image centre for two flights performed at different times for Mavic3E.

Analysing the graph (Figure 5), it can be seen that for both series the sharpness decreases as the distance from the centre of the image increases, a pretty natural phenomenon due to the optical properties of the camera. In addition, the capture time and the illumination have a strong influence on the image quality, as indicated by the decrease in resolving power with increased ISO. MTF10 values for R, G and B are similar within each data set.

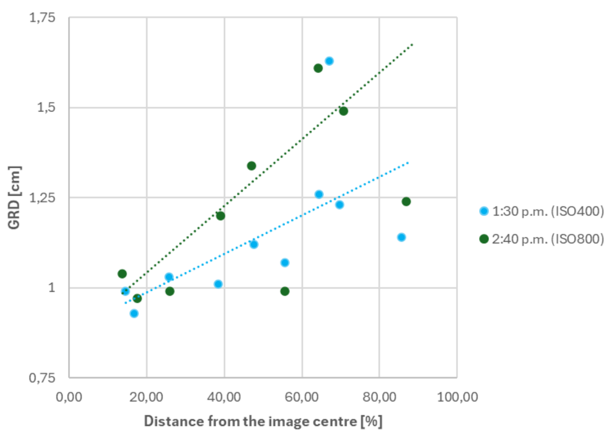

Figure 6. The values of MTF10 in relation to the distance from the image centre for two flights performed at different times for Mavic3E.

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3.2.2 Phantom 4 RTK

For the Phantom 4 RTK drone, three missions were made at constant altitude (GSD = 1 cm). The first was taken at 13:50 (ISO was 400), the second over an hour later at 15:00 (ISO = 1600) and the third at 15:15 (ISO = 3200). The influence of two factors was examined in this case – the time of day (including lighting and ISO) and the impact of the distance of the Siemens star from the image centre. As for the Mavic 3E, 10 images were selected from each mission. Below is a chart (Figure 7) of the MTF10 values for the three and the relationship against distance from the centre of the image [%]. The key observations are that in all three series, the MTF10 values decrease with increasing distance from the image centre, which is typical due to increasing distortion (influence of the optical system). In addition, all bands show a similar decrease in sharpness (optical resolution).

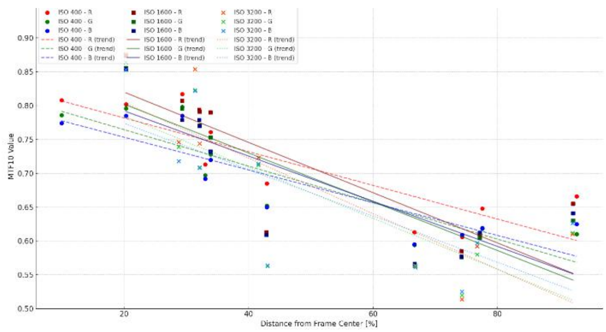

Figure 7. The values of MTF10 in relation to the distance from the image centre for flights performed for Phantom 4 RTK.

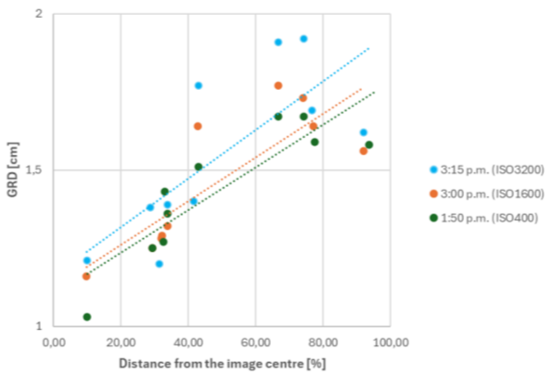

Figure 8. The values of GRD in relation to the distance from the image centre for flights performed for Phantom 4 RTK.

3.2.3 DJI Zenmuse P1

Eight missions were taken with the DJI Zenmuse P1 camera. Images for which the Siemens star was in different parts of the photo were similarly taken for analysis.

Again, the chart (Figure 9) shows a clear downward trend - the sharpness of the image (represented by MTF10) decreases as the distance from the centre of the image increases. It is particularly interesting to compare two series taken for the same area, but at different ISOs and at different times of day – the series at 12:55, taken at a very high ISO 1800, shows the lowest MTF10 values. In contrast, just 10 minutes later, at 13:05, another flight was carried out at ISO 400 and clearly higher MTF10 values were obtained. Such a discrepancy again highlights the importance of both appropriately chosen exposure parameters and lighting conditions (time of day), which have a significant impact on imaging quality.

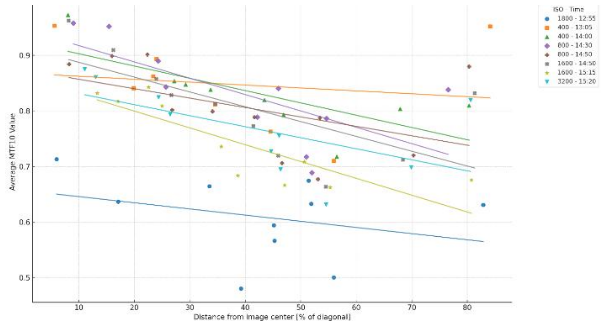

Figure 9. The values of MTF10 in relation to the distance from the image centre for flights performed for DJI Zenmuse P1.

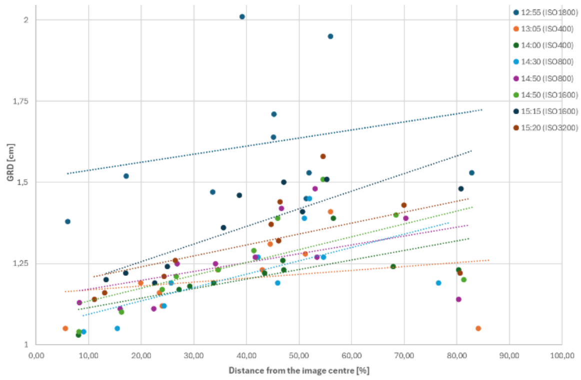

Figure 10. The values of GRD in relation to the distance from the image centre for flights performed for DJI Zenmuse P1.

3.3 Analysis of point clouds from dense image matching

For the analysis, 3D point clouds extracted from dense image matching were used. For two selected reference objects (gabled and flat concrete blocks), fragments of the point clouds were cut out. The distances of the cloud points relative to the reference planes were then calculated for each of the 13 flights (which were analysed in section 3.2). The mean values and standard deviations determined for each data set allowed the quality of the geometry representation to be assessed (Table 3).

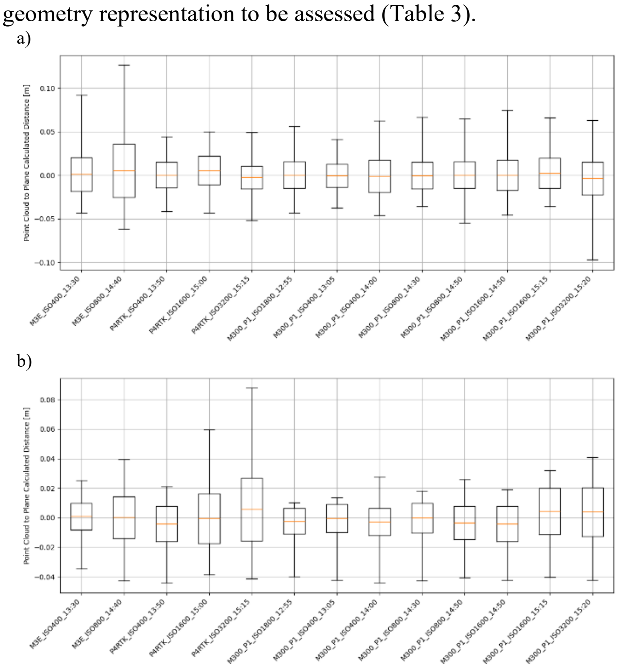

Figure 11. Distance values between reference planes and point clouds generated from dense matching of images from a series of

flights for three drones: DJI Mavic 3E, M300 with DJI Zenmuse P1, Phantom 4 RTK (a - object 1, b - object 2).

Based on the results, it can be said that for object 1 (the peak-like), the best result was obtained for the point cloud from the Phantom 4 RTK images (ISO 400) - the mean value of the distance of the cloud points from the reference plane was 0.0003 m and the standard deviation was 0.0147 m, and for the cloud from the P1 camera images (ISO400, 13:05) - the mean value of the distance of the cloud points from the reference plane was -0.0003 m and the standard deviation was 0.0134 m. Based on the visual analysis, these variants also show the most precise representation.

For the second object (concrete flat blocks), good results were achieved with both the Mavic 3E (ISO 400) and the M300 Zenmuse P1 for flights taken at the earlier part of the day. The graphs (Figure 11) show the point cloud distribution analysis results relative to the fitted plane. It is worth noting that the average values oscillated around a few millimetres, which generally indicates good reconstruction quality. Particularly for the second object, it can be seen that the standard deviation values for each of the three sensors increase with increasing ISO values and increasingly later hours of the flight.

Furthermore, by visually analysing the cross sections, it can also be seen that the dispersion of distance values relative to the reference plane confirms previous observations and conclusions. The analysis showed that the accuracy of the representation of planes in 3D point clouds depends on the quality of the input image, which is influenced by the noise level resulting from the settings as well as the camera optical system.

4. CONCLUSIONS

The research presented above extensively discusses the topic of imaging quality and optical resolution of images acquired using UAV platform cameras. The MTF10 index implemented in DLR's ResolvingPower software was used to quantitatively evaluate the optical resolution of the cameras. Test were focused on how various operational parameters such as flight altitude, ISO sensitivity, lighting conditions, and sensor type affect image quality.

From observing the relationship between ISO and the hour of image acquisition, it is easy to see that choosing the optimal photographic time has a huge impact on the optical resolution of the images. To capture a properly illuminated photo, imaging systems compensate for the lack of sunlight largely by manipulating the ISO. An increase in ISO leads to an increase in image graininess, which negatively affects MTF10 and GRD values (Figures 6-10). The image-derived 3D reconstruction deteriorate in quality as a result of increased image noise – as seen in Table 3. Lower ISO settings and better lighting conditions yielded more precise and less noisy point clouds, particularly evident in the standard deviation of distances from reference planes.

A decrease in optical quality with distance from the camera's optical axis was observed for all sensors tested. Due to the camera's optics and the phenomena of distortion and image aberration, MTF10 and GRD get worse the farther away from the center of the image.

Also worth noting is the significant difference in optical quality between the sensors in the Mavic 3E and Matrice 4E systems. Despite the very similar parameters of the cameras in both drones, a significant difference can be observed in the MTF10 values and the behavior of the index in relation to GSD (Figure 3). The apparent differences may indicate the introduction of sharpening by the camera on-board image processor between successive editions of DJI drones.

The insights presented in the article provide new information on UAV mission planning. In particular, the need to optimally select flight parameters depending on environmental lighting conditions is worth highlighting. Proper selection of flight parameters and camera settings allows for the acquisition of better quality images and 3D photogrammetric products such as point clouds and mesh models.

REFERENCES

Kedzierski, M., & Wierzbicki, D. (2015). Radiometric quality assessment of images acquired by UAV's in various lighting and weather conditions. *Measurement*, *76*, 156-169.

Lim, P. C., Kim, T., Na, S. I., Lee, K. D., Ahn, H. Y., & Hong, J. (2018). Analysis of UAV image quality using edge analysis. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *42*, 359-364.

Meißner, H., Cramer, M., & Reulke, R. (2019, November). Evaluation of structures and methods for resolution determination of remote sensing sensors. In *Pacific-Rim Symposium on Image and Video Technology* (pp. 59-69). Cham: Springer International Psublishing.

Meißner, H., Cramer, M., & Reulke, R. (2018). Towards standardized evaluation of image quality for airborne camera systems. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *42*, 295-300.

Meißner, H., Cramer, M., & Piltz, B. (2017). Benchmarking the optical resolving power of UAV based camera systems. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *42*, 243-249.

Orych, A. (2015). Review of methods for determining the spatial resolution of UAV sensors. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *40*, 391-395.

Schulz, J., Cramer, M., & Herbst, T. (2021). Evaluation of Phase One scan station for analogue aerial image digitisation. *PFG–Journal of Photogrammetry, Remote Sensing and Geoinformation Science*, *89*(5), 461-473.

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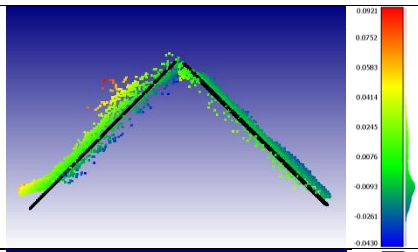
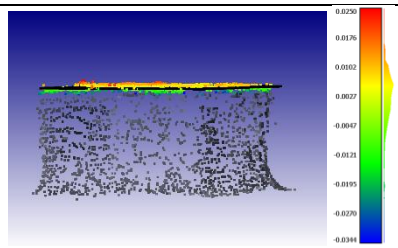
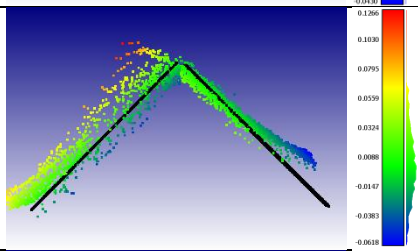
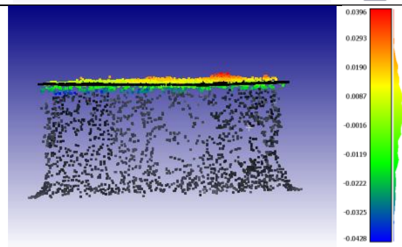
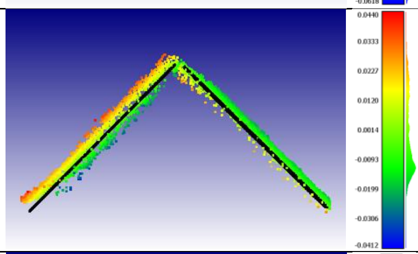
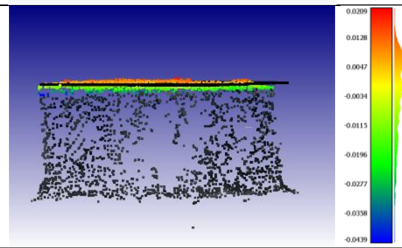
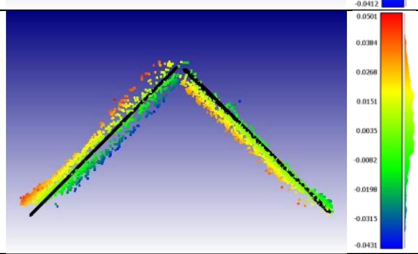
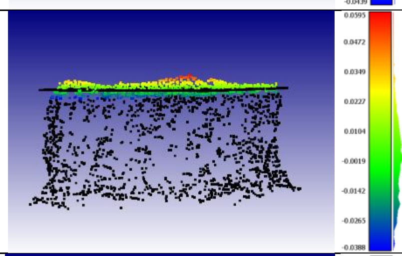
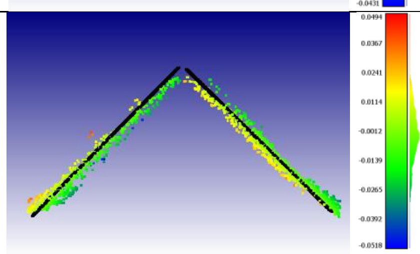
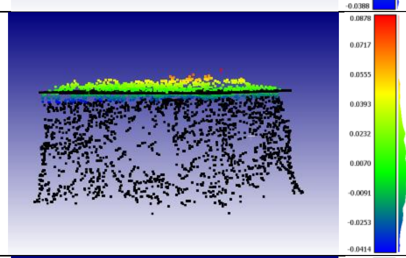
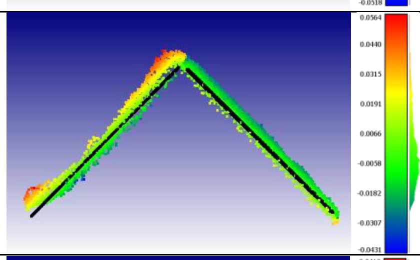
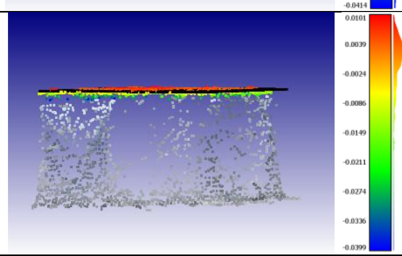
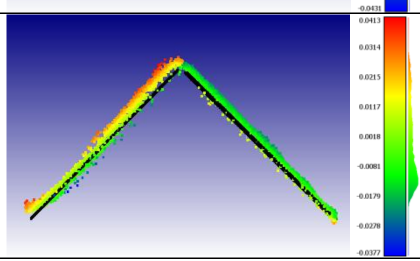
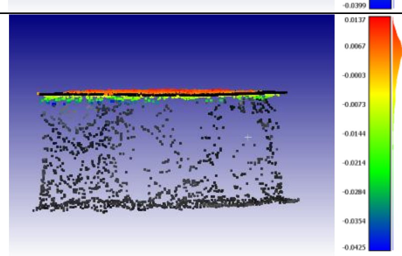
Sensor	ISO	H	GRD avg	MTF avg	Object 1	Object 2
M3E	400	13:30	1,14	0,897		
M3E	800	14:40	1,31	0,814		
P4 RTK	400	13:50	1,44	0,712		
P4 RTK	1600	15:00	1,46	0,699		
P4 RTK	3200	15:15	1,55	0,663		
M300 P1	1800	12:55	1,62	0,627		
M300 P1	400	13:05	1,20	0,838		

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https://doi.org/10.5194/isprs-archives-XLVIII-1-W4-2025-139-2025 |

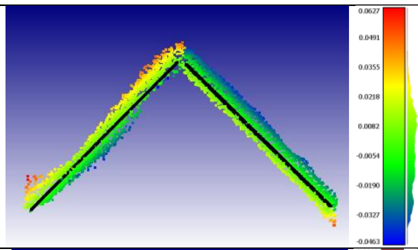
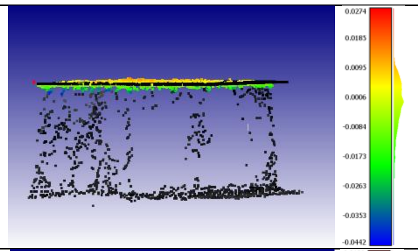
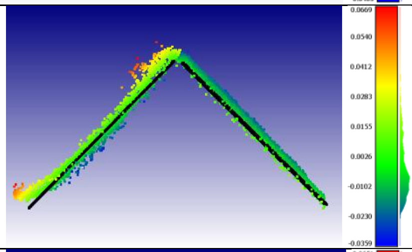
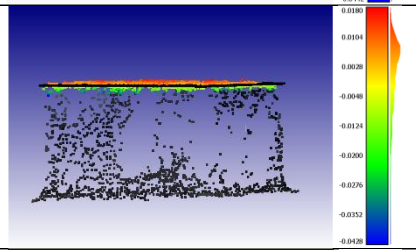
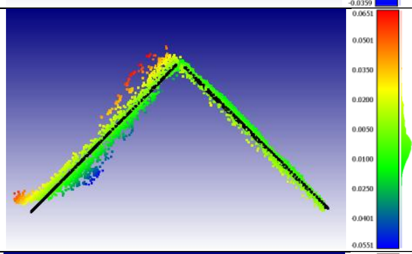
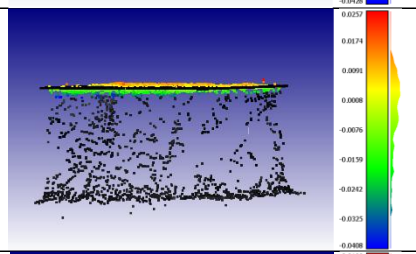
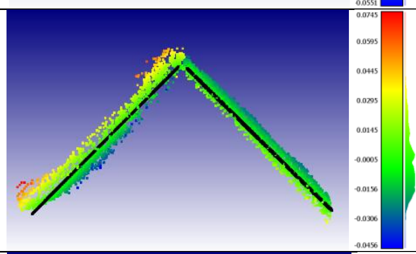
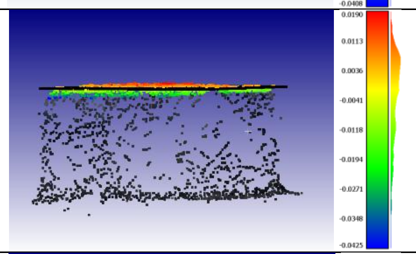
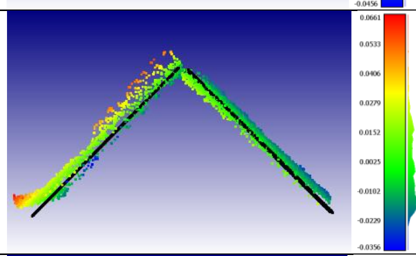
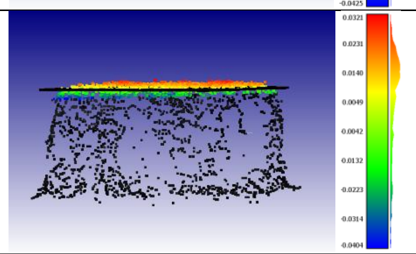
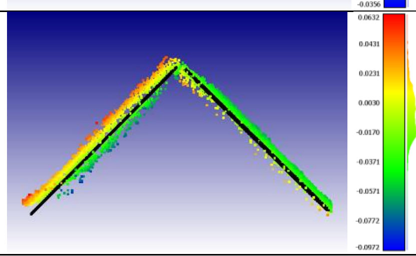
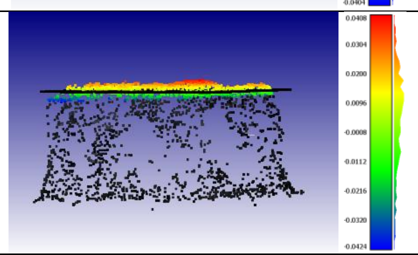
M300_P1	400	14:00	1,21	0,803		
M300_P1	800	14:30	1,22	0,830		
M300_P1	800	14:50	1,26	0,804		
M300_P1	1600	14:50	1,25	0,807		
M300_P1	1600	15:15	1,36	0,744		
M300_P1	3200	15:20	1,31	0,768		

Table 3. Visualisation of the point cloud deviations relative to the reference plane for two test objects (object 1 – gabled, object 2 - flat concrete block) registered by different UAV cameras at different ISO settings and at different times of day. The colours represent differences in distance from the reference plane (black).

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