Review of Phase One iXM-RS280F Bayer Pattern Effective Resolution

Karsten Jacobsen[1] · Regin Møller Sørensen[2] · Sven Schöbel[3]

Abstract

This study explores effective resolution in Bayer pattern images through a comparative analysis of different methodologies. Bayer pattern technology, characterized by its 2x2 pixel arrangement, was introduced in Phase One Cameras in 1998. This technology is now the standard for airborne cameras, and we verify both the theoretical and actual quality through several tests. The investigation leverages various techniques to assess image sharpness and resolution. Test data was collected using aerial surveys from different altitudes. Two complementary methods were employed to evaluate resolution: a Siemens Star-based MTF analysis using the DLR "Resolving Power" tool, and an edge profile-based method relying on grey value gradients across building shadows and other structural transitions. Results indicated that advanced demosaicing algorithms achieve nearly equal resolution across all color channels, with the blue channel occasionally outperforming the green due to shorter wavelength, despite originally higher number of green pixels. While Siemens Star analysis yielded localized MTF10 measurements, its practical use was limited by overexposure, directional reflections, and uneven target quality. In contrast, the edge analysis offered a more comprehensive evaluation across the image plane, revealing effective resolution factors of up to 1.04. A subsequent laboratory-based collimator test confirmed that observed artifacts in Siemens Star images were unrelated to the sensor, validating the consistency of in-flight resolution measurements. The research underscores the importance of considering both sensor technology and external factors in resolution assessments. The investigation confirmed very good image quality of the Bayer pattern camera with an effective ground sampling distance (GSD) close to the nominal GSD.

Keywords Image quality · Bayer pattern · Phase One camera· Siemens Star · MTF · effective resolution

Zusammenfassung

In dieser Studie wird die effektive Auflösung in Bayer-Pattern-Bildern durch eine vergleichende Analyse verschiedener Methoden untersucht. Die Bayer-Pattern-Technologie, die sich durch ihre 2x2-Pixel-Anordnung auszeichnet, wurde 1998 in Phase One-Kameras eingeführt. Diese Technologie ist heute der Standard für Luftbildkameras, und wir überprüfen sowohl die theoretische als auch die tatsächliche Qualität durch verschiedene Tests. Die Untersuchung nutzt verschiedene Techniken zur Bewertung der Bildschärfe und Auflösung. Die Testdaten wurden mit Hilfe von Luftaufnahmen aus verschiedenen Höhen gesammelt. Zwei sich ergänzende Methoden wurden zur Bewertung der Auflösung eingesetzt: eine MTF-Analyse mit Siemens-Stern unter Verwendung des DLR-Tools „Resolving Power" sowie ein kantenbasiertes Verfahren, das auf Grauwertverläufen an Gebäudeschatten und anderen strukturellen Übergängen basiert. Die Ergebnisse zeigen, dass fortschrittliche Demosaicing-Algorithmen eine nahezu gleiche Auflösung über alle Farbkanäle hinweg erreichen, wobei der blaue Kanal aufgrund der kürzeren Wellenlänge gelegentlich besser abschneidet als der grüne, obwohl die Zahl der grünen Pixel ursprünglich höher war. Während die Siemens-Stern-Analyse lokal begrenzte MTF10-Werte lieferte, war ihr praktischer Nutzen durch Überbelichtung, gerichtete Reflexionen und ungleichmäßige Zielqualität eingeschränkt. Die Kantenanalyse bot hingegen eine umfassendere Bewertung über die gesamte Bildebene hinweg und zeigte effektive Auflösungsfaktoren von bis zu 1,04. Eine anschließende laborbasierte Kollimatormessung bestätigte, dass beobachtete Artefakte in den Siemens-Stern-Bildern nicht auf die Kamera selbst zurückzuführen sind, was die Konsistenz der Auflösungsmessungen zusätzlich untermauerte. Die Untersuchung unterstreicht, wie wichtig es ist, bei der Bewertung der Auflösung sowohl die Sensortechnologie als auch externe Faktoren zu berücksichtigen. Die Untersuchung bestätigt eine sehr gute Bildqualität der Bayer-Pattern Kamera mit einer effektiven Objektpixelgröße nahe der nominellen Objektpixelgröße.

Karsten Jacobsen
jacobsen@ipi.uni-hannover.de
Regin Møller Sørensen
remam@kds.dk
Sven Schöbel
ssc@phaseone.com
[1] Institut für Photogrammetrie und Geoinformation, Leibniz Universität Hannover, Germany
[2] Klimadatastyrelsen (earlier: Styrelsen for Dataforsyning og Infrastruktur), Copenhagen, Denmark
[3] Phase One, Frederiksberg, Denmark

1. Introduction

1.1 Bayer Pattern

The concept of a Bayer Pattern is a 2x2 pixel pattern of two green pixels and one red and one blue each. In relation to a pan-sharpening sensor with 3 times larger color pixels than panchromatic pixels, the ratio of Bayer-pattern green pixels to pan-sharpening pixels is 4.5 : 1 and for red and blue pixels the relation is 2.25 : 1 (Fig. 1).

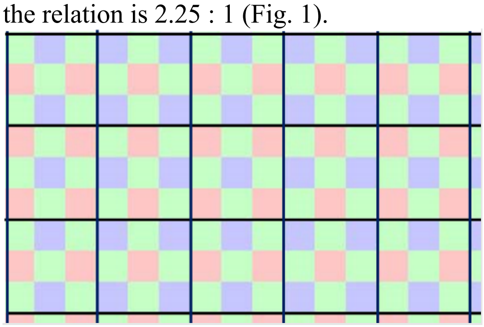


Figure 1 *Relation of color pixels of pan-sharpening sensor with linear factor 3 between color and panchromatic pixel (solid lines) and Bayer-pattern pixels (colored pixels)*

As illustrated in Figure 1 no band has the full resolution, and it has been disputed that Bayer pattern leads to a degradation of the effective GSD (Ground Sampling Distance). This is only true if no demosaicing is performed. Demosaicing is the process to obtain the full resolution in all three bands. The fact that the intensity of the color bands is highly correlated is one factor amongst others that advanced demosaicing algorithms use to achieve full resolution, enlarging the number of original color pixels by factor 2 or 4. The demosaicing is a restoration problem, solved by minimizing the difference between the input raw image and the sampled full-color result.

Traditional multi-head systems have been used in the past for aerial surveying. These setups employed separate sensors with relatively low resolution for each color channel, along with an additional high-resolution panchromatic sensor. The resulting images were then merged using pan-sharpening techniques to produce a high-resolution, full-color image. In contrast Bayer pattern cameras offer several advantages over traditional multi-sensor setups that rely on separately captured color and panchromatic images:

- Cost-effective: Single-sensor design reduces manufacturing costs; makes cameras more affordable for users.
- Faster image processing: Less data to process compared to multi-sensor systems; results in quicker image capture and processing.
- Improved reliability: Fewer points of failure compared to multi-head systems; increases overall camera durability.
- Consistent color reproduction: Single sensor ensures uniform color capture; avoids color discrepancies between multiple sensors.

1.2 General remarks on influence factors for aerial mapping data collection

The theoretical effective GSD is influenced by numerous factors other than sensor technology.

A camera is a system composed of multiple components, with the lens playing a particularly critical role in determining the effective ground sampling distance (GSD). The effective GSD is further influenced by how well the image sensor captures the lens' optimal region and by the overall stability of the camera system.

Finally, certain external factors present during image capture might influence the effective GSD, such as

- Camera settings – Settings to use the optimal part of the lens (aperture), and ensure enough light for the exposure (shutter speed).
- Post processing. Making sure not to lose valuable information while processing the imagery to the output format
- Airplane influences such as vibrations and turbulences
- Light conditions such as sun angle and front light
- Atmospheric conditions such as moisture or haze

This list is not exhaustive, but it can be concluded that various physical and human factors influence the effective GSD of all cameras. The theoretical effective GSD based on the sensor technology alone is different from the effective GSD measured in the image.

Practical experience from SDFI (The Danish Agency for Data Supply and Infrastructure), indicates that the influence of these factors must be taken in consideration when judging the quality of the aerial imagery captured by modern digital sensors. Objective and standardized tools and targets for evaluating the effective GSD would be very helpful.

2. Test data set description

The test data was collected at two different resolutions, 5 cm and 10 cm GSD, using nadir imagery. The test area, the AdV-test field Neumünster, located in Northern Germany, includes a Siemens Star target.

Figure 2 Siemens Start target in the test area

The mission was flown on June 3, 2023. For the 5 cm mission the first capture was taken at 8:33 a.m. UTC+2 and the last at 9:20 a.m. UTC+2, resulting in sun angels ranging from 28.8° to 35.6° The 10 cm resolution imagery capture began at 9:31 a.m. UTC+2 and concluded at 10:09 a.m. UTC+2, with sun angles ranging from 37.2° to 42.6°. The initial sun angles for the 5 cm imagery were suboptimal for aerial image capture, potentially causing longer and darker shadows and semi-ideal light reflection angles. Additionally, the image quality and resolution were influenced by slightly suboptimal chosen exposure parameters.

The Camera System used for this test flight is a PAS 880i (S/N OB00021). The large format aerial system comprises a nadir 280MP RGB, a nadir 150MP NIR and four 150MP oblique cameras integrated into a single pod to capture photogrammetric nadir and oblique images simultaneously. The analysis in this paper focuses on images acquired by Nadir RGB Camera iXM-RS280F (S/N YZ000037).

The data set has been post-processed using Phase Ones software package iX Process. During processing, a common aerial mapping workflow followed, and the raw imagery has undergone advanced demosaicing and stitching.

3. Siemens Star analysis

Sharpness and effective resolution can be evaluated in different ways. One way that was chosen to create comparable results is using the DLR tool called "Resolving power", included in the DLR MACS-Box. that is specifically designed to evaluate images with Siemens Stars. The tool produces results in the form of MTF10 values, which is the line frequency at which 10% contrast remains. The Siemens star in the test area has a diameter of ~ 6.8m with 12 black and white segments. It is painted on a plastic tarp and laid out on a lawn. This leads to locally changed grey values due to directed reflection. It shows a grey value variation up to 15 % in the bright segments and a tendency of over-exposition, and in the dark segments a grey value variation up to 35%.

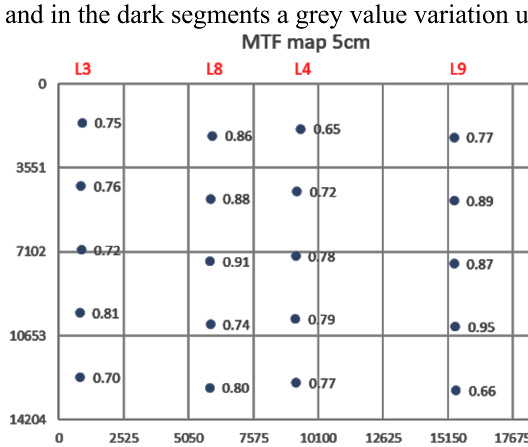


Figure 3 MTF map for imagery with 5cm GSD

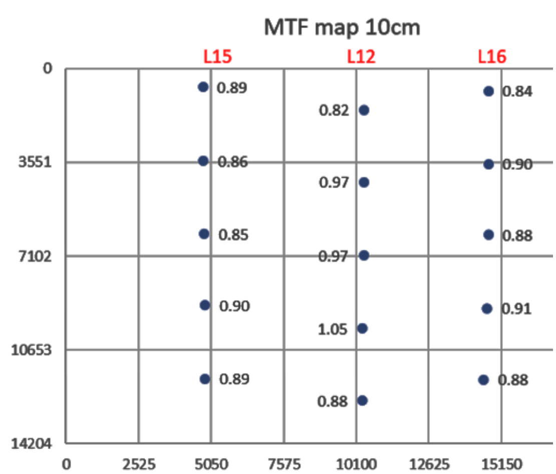


Figure 4 MTF map for imagery with 10cm GSD

Analysis of the Histogram at the area of the Siemens Star indicate an oversaturation of the raw data. That is in our belief a source for improper results using the DLR tool. Hence the images for this analysis were reprocessed with a negative exposure correction, to bring the analyzed Siemens star out of saturation.

Figures 3 and 4 present the MTF10 results calculated using the Resolving Power Tool. The values are displayed in an XY graph showing the location of the Siemens star in the overlaid images. In this way, sharpness can be evaluated as a function of location in the image. The Red L-numbers are the flight line numbers. The flight lines were captured in ascending order.

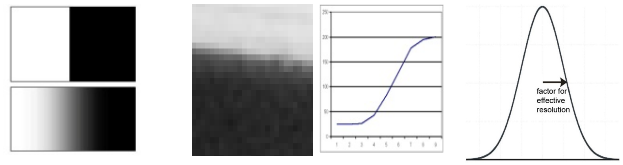
The MTF-values derived from the 10 cm images (Fig. 4) are slightly larger than those from the 5cm images (Fig. 3). Upon visual inspection, there is no discernible difference in actual sharpness between the two sets of images. The difference in the sun angle between the two flights, combined with the characteristics of the Siemens star, could significantly impact the measurements. This discrepancy raises concerns regarding the validity of this measurement as an absolute indicator of sharpness. Another concern is the limitation of the Siemens Star target only available for measurements once in a scarce number of images of an aerial flight over a test area. For the 10cm GSD flight the Siemens Star is represented in 15 images (6% of the entire data set of 256 images). In the 5cm data set the Siemens Star is included in 25 images (4% of the entire test data set of 629 images).

The above shows the disadvantage of the Siemens Star as only one measurement of each Siemens Star in single images is possible, which result is directly depending on definition of circle diameter, whereas the diameter is in some cases depending on a not sharp circle.

In this study the edge analysis is preferred due to more and better edges, mainly at shadows of buildings on flat and homogenous ground.

4. Effective resolution analysis

The effective image resolution can be determined based on the grey value gradient at edges in the image – corresponding to sudden changes in grey values in the object space. Caused by the optical transfer function, the clear profile in the object space is converted into a continuous change in the grey values at the location of the edge in the image.



Above: grey value in object space Below: grey value in image | Edge in digital image iXM-RS280F | Averaged grey value profile across edge (ESF) | Differentiation → edge spread function with factor for effective resolution (LSF)

Figure 5 *Basic principle of edge analysis*

The differentiation of the average grey value profile in the image leads to the edge spread function. The width of the edge spread function determines the effective image resolution (Fig. 5). The factor of the effective resolution multiplied by the GSD results in the effective GSD or image resolution.

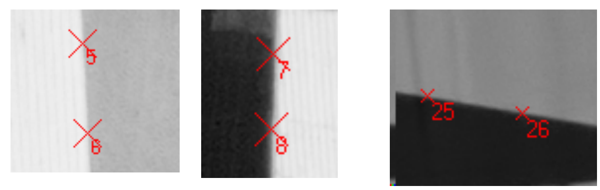


Figure 6 *Examples of used edges*

Not one single grey value profile is used, but the average of a higher number of grey value profiles perpendicular to the edge between the two specified edge points (Fig. 6).

4.1 Campaign 1

The first measurement campaign analyzed five images with a GSD of 10 cm and ten images with a GSD of 5 cm. DLPX software, a tool developed for the precise determination of image positions in digital images by the Leibniz University of Hannover/Jacobsen, was used for the measurement process. The tool allows handling of large images by dividing them into sub-images, which can be handled fast and providing tools for precise profile placement. To determine a precise point position in the image the recommended zoom level of 300% was used.

The resulting listing of profiles has been used in the analysis tool EDGE. This command base program, developed by the Leibniz University of Hannover/Jacobsen, analyzes averaged grey value profiles. It is using an average of 30 – 60 profiles perpendicular to each edge. If the profiles are not located exactly in line or column direction, the grey values are transformed to the location of the required profiles – this will be respected for the analysis. This analysis involved examining the intensity transitions of the profiles. Descriptive statistics and spatial distribution patterns were computed to provide insights into the sensor's behavior.

The images used in this campaign show the Siemens star of the test area. Between 8 and 10 edges were analyzed in each image and about 40 profiles are averaged for each edge. Based on these 8 to 10 edges used in each processed image, the standard deviation of the effective resolution is between 0.02 and 0.04 or 2% to 4%.

The average factor for the 5 images used with 10 cm GSD is 1.04 for the red channel, 1.04 for the green channel and 1.02 for the blue channel with a standard deviation for the mean of 0.01 (Fig. 7).

For the 10 images used with 5 cm GSD, the factor for effective resolution is 1.03 for the red channel, 1.01 for the green channel and 0.99 for the blue channel with the same standard deviation for the mean of 0.01. For both GSD combined, the average of images was 1.03 for the red channel, 1.02 for the green channel and 1.00 for the blue channel or regardless of the color channel 1.02.

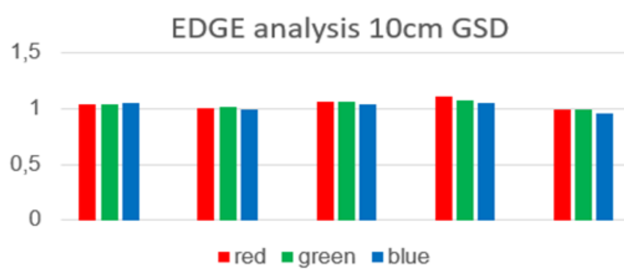


Figure 7 *Factor for effective resolution of five analyzed images*

The effective resolution for the 10 cm GSD images translates to an effective GSD of 10.4 cm for red, 10.4 cm for green and 10.2 cm for blue. For the 5 cm GSD images, the effective GSD is 5.15 cm for red, 5.05 cm for green and 4.95 cm for blue. The slightly better result for the blue channel aligns with the theory that shorter wavelengths provide better resolution.

The effective resolution must be seen in relation to the diffraction limited resolution, named also diaphragm limited resolution, – the size of an infinitive small light source spread to an airy disc with a diameter by the diffraction in the image space. Corresponding to formula (1) it is linear to the wavelength. An image point can never be smaller than the airy. This relation explains the slightly better result for the blue band.

Diameter of airy disc = 2.44 * f-number * λ (1)

formula modified from Hallows and James 2024, https://en.wikipedia.org/wiki/Diffraction-limited_system

f-number	λ=0.44µm (blue)	λ=0.55µm (green)	λ=0.65µm (red)
4.0	1.8 µm	2.2 µm	2.6 µm
5.6	2.5 µm	3.1 µm	3.6 µm
8	3.5 µm	4.4 µm	5.2 µm
11	4.8 µm	6.1 µm	7.2 µm

Table 1 *Diameter of airy disc based on diffraction limited resolution*

The effective resolution was also measured on the Siemens Star itself in five images with 10 cm and ten 10 images with 5 cm GSD of the original processed imagery.

10 cm GSD: factor for effective resolution

blue	green	red
1.11	1.13	1.10

5 cm GSD: factor for effective resolution

blue	green	red
1.23	1.23	1.20

Table 2 *Effective Resolution measured on Siemens Star in overexposed imagery*

Two main issues can be identified. First, the entire dataset was processed to achieve a uniform and balanced radiometric appearance across the test block, with a focus on generating visually consistent photogrammetric products. However, this optimization was not tailored for the Siemens Star images, resulting in a tendency for them to appear overly bright. Second, the Siemens Star target itself is not perfectly flat, exhibits directional reflections, and has visible dirt in some areas, all of which can affect image quality.

4.2 Campaign 2

The input data for the second edge measurement campaign were images with a GSD of 5 cm. The campaign was conducted on five well-distributed images to ensure comprehensive spatial coverage and minimize potential biases. Each image was divided into a 10x7 grid, ensuring systematic sampling across all sections. Within each grid section, the aim was to determine the effective resolution at one to two edges, capturing the variation in edge characteristics throughout the image and examining the influence of contrast, rotation, and location within the image.

Profiles were strategically placed at objects exhibiting edges between light and dark grey values. This placement was manually determined to ensure accuracy and relevance of the selected edges. The focus on clear edges allowed for precise measurement of intensity transitions, which are critical for the study. The measuring method described in the previous chapter was used in this campaign too.

The measurements have undergone blunder detection by removing outliers that are not related to the camera sharpness. A filter value of 1.3 has been used because most of the measurements are below this threshold. The values of edge measurement for each single-color band were averaged. Altogether 587 edges have been used for the final analysis covering all 70 grid areas of the image plane (Fig. 8).

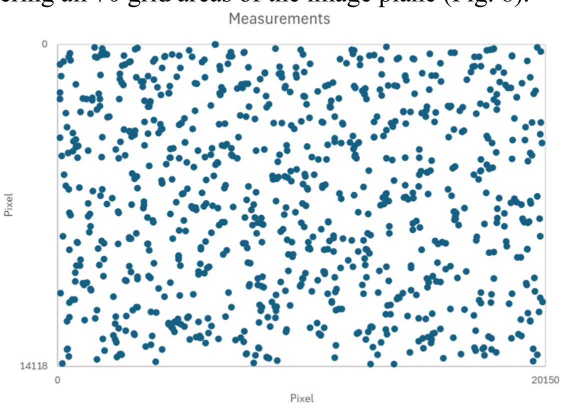


Figure 8 *Overlaid location of used edges in the images*

All Edge measurement values for each grid cell have been averaged per band resulting in a factor for effective resolution for each color band. These grid values per color band have been averaged to show the effective resolution scale factor for RGB. It shows an average of 1.00 with a Standard deviation of 0.062.

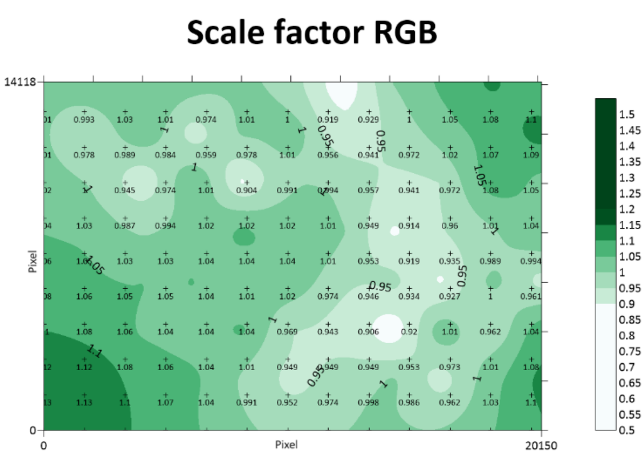


Figure 9 *Plot of effective resolution factor for 5cm RGB*

The distribution of the values follows the expected behavior of higher sharpness in the center of the image and slight drops of sharpness at the edges of the image plane. The right side of the image plane shows a higher sharpness, which indicates minor difference in the sharpness behavior of the two cameras used for the stitched image plane.

The comparison of the effective resolution values for the imagery with 5 cm GSD measured in Campaign 1 and Campaign 2 shows the same satisfying range of effective sharpness (Tab. 3).

Effective resolution	red	green	blue	RGB
Campaign 1	1.03	1.01	0.99	1.02
Campaign 2	1.03	1.00	0.98	1.00

Table 3 Effective resolution factors of both campaigns

Theoretically, the effective resolution factor should be at least 1.0, but it can be reduced by image sharpening. This was the case with the first data set handled, which showed typical parallel lines at edges. For this reason, the data set was reprocessed, and no signs of image sharpening were seen in the reprocessed dataset.

5. Collimator measurement

When analyzing the Siemens star present in the image with 5cm GSD, a slight blurring was observed locally at the pixel area x=2.000, y=10.000 on the image sensor in single images. This observation was not present in the effective sharpness measurements. To validate this, finding an independent sensor analysis under laboratory conditions was initiated.

To demonstrate that the observed blur is not due to the camera system, we subjected the nadir camera from the test setup (Nadir RGB Camera, S/N YZ000037) to a focus assessment using a Trioptics Image Master Universal collimator (Fig. 10).

Figure 10 *Trioptics collimator under laboratory conditions*

This device precisely measures the two-dimensional focus field of each of the two identical camera heads comprising the nadir camera. Each sensor is positioned to cover one half of the image circle exclusively. Given the substantial size of the image circle, it is unnecessary to tilt the cameras, thereby avoiding perspective distortion.

As result of this measurement, a plot of the Modulation Transfer Function (MTF) is created (Fig. 10). The MTF measures an optical system's ability to transfer a contrast to an image using spatial frequency. In this measurement the MTF value is at 50 lp/mm measured across the 2D image field. For simplicity, the presentation in the plot is unit-less and shows an average of Sagittal and Tangential MTF results.

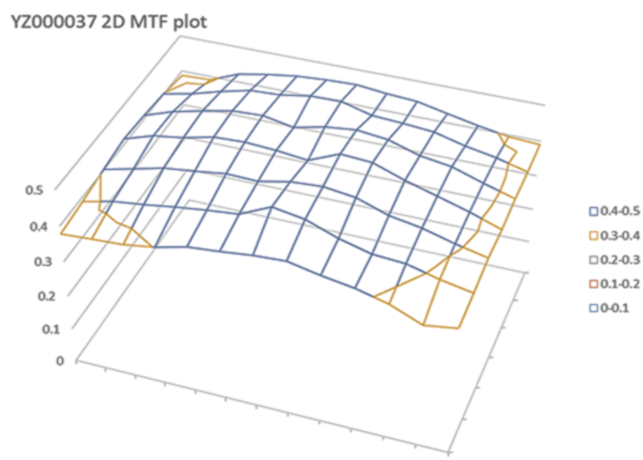


Figure 11 *MTF variation in image of iXM-RS280F camera*

As expected, there is a minor decline in sharpness from the optical center to the corners, which is typical. However, no local decline in sharpness was detected in the region of the image where the blurry Siemens star was observed. This finding supports the hypothesis that the blurriness originated from factors unrelated to the camera system itself.

Summary

Today, state-of-the-art cameras with Bayer pattern sensors for photogrammetry are used. For demonstration of the potential of Bayer pattern images a Phase One PAS 880i camera flight over the ADV-test area Neumünster was conducted, of which the 5cm and 10cm images from the RGB Nadir looking cameras were analyzed. The test site is equipped with a Siemens star target. The analysis of the images showing the Siemens star did not lead to optimal results, potentially explained by overexposed processing of the imagery showing the Siemens star, causing strong grey value changes in the bright and even more in the darker parts of the Siemens star. More suitable is the use of edge analysis. Straight edges are available with higher numbers at shadows of buildings on homogenous and flat ground. The edge analysis resulted in factors for effective resolution not exceeding 1.04, meaning that the effective resolution does not exceed 5.2 cm for 5cm GSD and 10.4 cm for 10 cm GSD images. This factor is also influenced by the flight conditions, which seem to be negligible. The factor for effective resolution is slightly better for the blue band than for green. This demonstrates that even the original double number of green pixels against blue pixels has no advantages after the demosaicing, or reverse, the demosaiced images have no disadvantage against original separate images with the full resolution.

Declaration

Acknowledgements The authors acknowledge the support by Phase One and the Working Committee of the Surveying Authorities of the Laender of the Federal Republic of Germany (AdV).

Funding The evaluation was funded by Phase One

Conflicts of interest/Competing interests The authors declare no conflicts of interest.

Availability of data and material The datasets have been distributed by Phase One.

Code availability The used program EDGE of the Leibniz University Hannover is available on request. For the Siemens star analysis the DLR tool Resolving power was used.

Authors' contributions Conceptualization: Edge analysis by Karsten Jacobsen, use by Sven Schöbel: Siemens star analysis and additional edge analysis by Sven Schöbel and Regin Møller Sørensen: Collimator analysis by Sven Schöbel.

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