Advantages of Customized Optical Design for Aerial Survey Cameras

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ABSTRACT

There is a long history in aerial survey cameras at Carl Zeiss. A number of requirements for aerial survey cameras differ significantly from standard photographic lenses. In order to achieve the best possible performance for aerial survey cameras costumized optical designs are necessary.
The paper gives a short historical background of aerial survey lenses from Carl Zeiss. It then discusses requirements that makes a costumized optical design not only beneficial, but necessary for high end aerial survey lenses.
First requirement for aerial survey cameras is a performance up to the spatial frequencies that are defined by the individual pixelsizes of the sensor. Second requirement is a performance very close to the theoretical design performance within the entire working environment. Thermal and pressure simulation results for a photographic lens and aerial survey lenses are presented and discussed for this purpose. Third requirement for aerial survey cameras is an as-buildt-performance very close to the theoretical design performance. We present monte-carlo-simulations of as-build-performance data and compare them with measured performance data for a large number of lenses.
It is concluded that a customized optical design ensures a uniqly stable, high performance lens that is perfectly suited for the most demanding aerial survey camera requirements.

1. HISTORICAL BACKGROUND OF AERIAL SURVEY LENSES FROM CARL ZEISS

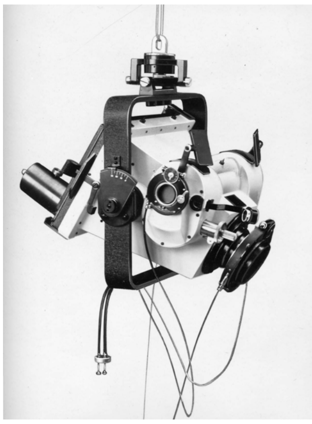

Fig. 1: Balloon camera Carl Zeiss Jena (1910).

Fig. 2: RMK-D optics by Carl Zeiss (2009).

Carl Zeiss has been manufacturing cameras for scientific photogrammetry ever since 1901. Carl Pulfrich (1858-1927) is closely associated with the early products. Ernst Wandersleb (1879-1963) took in 1905 shoots from a balloon with the Zeiss Tessar lens designed by Paul Rudolph (1858-1935) [1]. The first balloon camera enabling photogrammetric images (Fig.1) has been built by Carl Zeiss in 1910. It was the first in a long tradition of high performance aerial survey cameras. In 1933 Robert Richter designed the Zeiss Topogon. It covered a large field of view with very small distortion values. Its symmetric design with a minimum of lens elements made it very robust with respect to tolerances by the production process and the environmental conditions. This unique combination of advantages made it the standard aerial lens for more than 20 years [2]. After 1945, Carl Zeiss developed in Jena and Oberkochen independently the well known LMK and RMK Systems. Both Systems used customized lens designs that derived from the Zeiss Topogon. After the reunification one of the first digital aerial survey systems, the DMC, was developed by Z/I Imaging and successfully brought to the market [3]. The lenses developed and manufactured by Carl Zeiss in Jena had been again designed to meet the stringent requirements of the costumer. Very recently the first prototype of the RMK-D system also developed by Intergraph Z/I has been introduced [4]. Again a customized optical design was required to meet the considerably increased demands on the lens performance.
The aerial survey lenses developed by Carl Zeiss within the last 100 years more then fulfilled the customer requirements. Something which will also be aimed for the aerial enses to be developed in the future.

2. CUSTOMIZED OPTICAL DESIGN MATCHING THE SENSOR PROPERTIES

The requirements for aerial survey camera lenses are derived from the overall system performance specifications. The sensor properties are closely linked to the optical design requirements if the system is supposed to work at its physical limits without introducing digital artifacts.

In order to have a measure of the image quality the Modulation Transfer Function needs to be introduced [5]. If an image has the extreme value I_{max} and I_{min} for the intensity, the contrast or visibility of the image is defined as $V = (I_{max} - I_{min}) / (I_{max}+I_{min})$ (1).

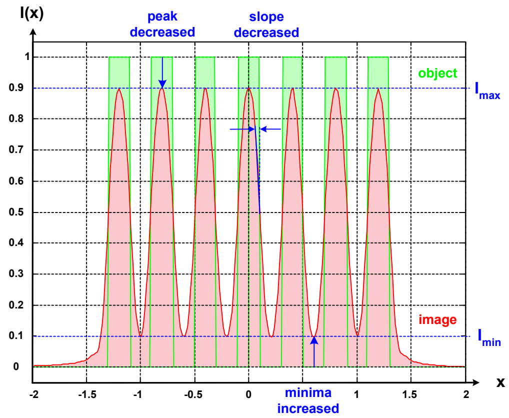

Fig. 3: Sketch of a grating image and reduction of contrast [6].

In reality the contrast decreases due to a reduced quality of the system, and if the feature size of the object details approaches the resolution limit.

Since a photogrammetric object can be thought of a superposition of line images of different orientation and feature size, the Modulation Transfer Function (MTF) of an optical system describes the visibility as function of feature size and feature orientation up to the resolution limit of the optical system. The feature size (p) is indirectly proportional to the spatial frequency the MTF refers to:
$\upsilon = 1/2p$ [LP/mm] or [cyc/mm] (2).

Here 1 cycle corresponds to one line pair with line width p.
The diffraction resolution limit of an optical system is given by $\upsilon_{max,o} = NA/2\lambda$ (3).

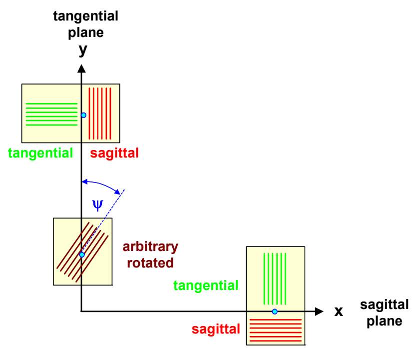

Fig. 4a: Orientation of the structure in the object.

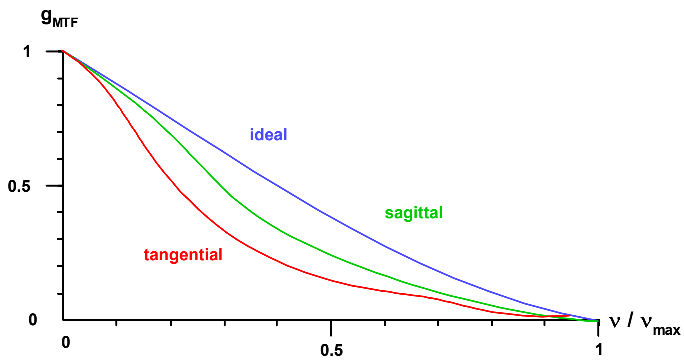

Fig. 4b: Modulation transfer for tangential and sagital orientation of structures in the object and reference to the ideal transfer curve.

Typically the sensor is supposed to limit the resolution of the system. From the pixel size (p) the resolution limit of the system limited by the sensor can be derived as
$\upsilon_{max,s}$ =1/(2p) [LP/mm] (4).

The Shannon-Nyquist theorem states that using a digital sensor with pixel size p and therefore a maximum resolution of 1/p the image must only consist of frequencies < 1/2p [LP/mm] to be imaged without artifacts [6]. This limiting frequency is known as the Nyquist frequency. The requirement for the optical system to allow high contrast and high resolution imaging without digital artifacts is to allow for maximum contrast transfer up to the Nyquist frequency and dampen the contrast considerably for frequencies higher than the Nyquist frequency. For aerial survey lenses a typical requirement is therefore a contrast in excess of 40% at half the Nyquist frequency and contrast values below 40% at frequencies twice the Nyquist frequency.

Within the next sections two custom optical designs and a state of the art photographic lens design are compared with respect to their optical performance.

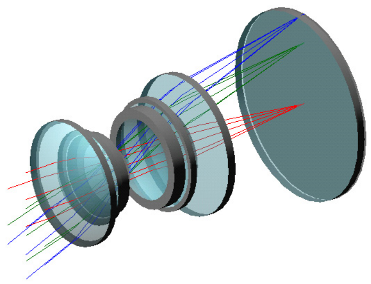

Fig. 5a: DMC PAN Lens.

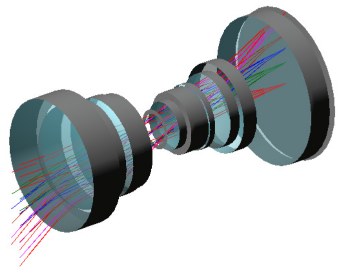

Fig. 5b: RMK-D Lens.

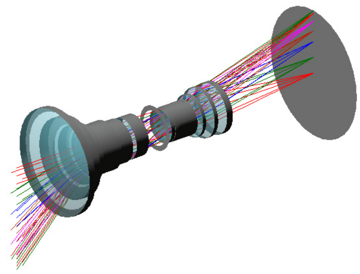

Fig. 5c: State-of-the-art photographic lens.

Figures 5a-c three lens designs analyzed in more detail below.

The DMC PAN – Lens (Fig. 5a) was custom designed for a 12um pixel size sensor. It provided for a large number of systems over years imaging quality that was only limited by the digital sensor [7]. The Nyquist frequency due to the pixel size is (according to Eq. 4) 42LP/mm, the 50% Nyquist frequency is 21LP/mm and twice the Nyquist frequency is 84LP/mm. Figure 6a) shows the modulation transfer function for discrete field points as a function of the spatial frequency. The three frequencies are indicated as well as the 40% contrast criteria. Figure 6b) is a somewhat different representation of the same modulation transfer function. In this representation the MTF is shown as a function of field size (position at the sensor) and this is done for three discrete spatial frequencies, which are again the 50% Nyquist(green), the Nyquist(blue) and the 2xNyquist frequency(pink). Again the 40% criteria are also indicated.

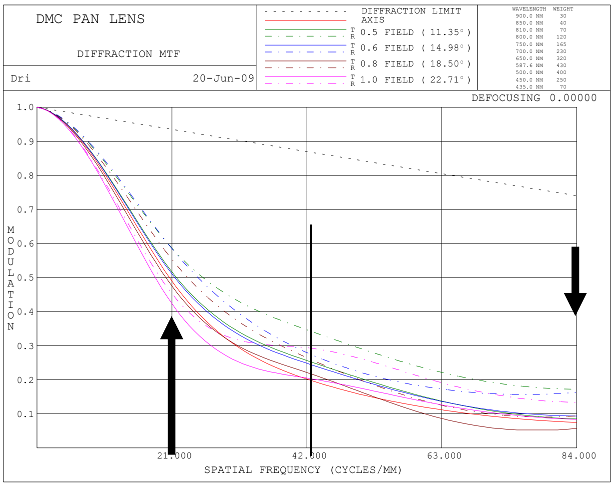

Fig. 6a: MTF as a function of υ for 6 field points for DMC PAN Lens.

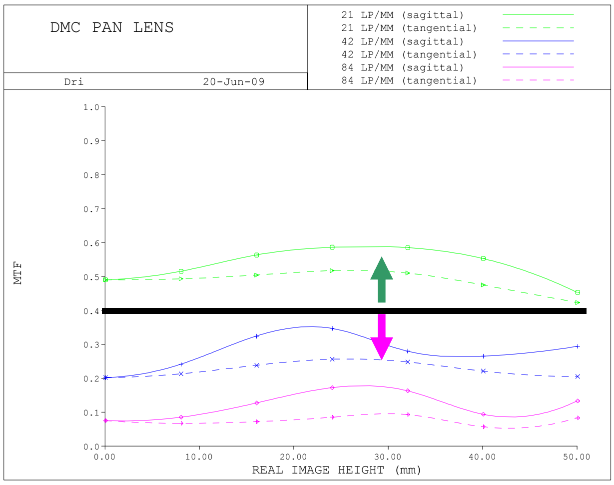

Fig. 6b: MTF as a function of field points for 3 υ (50% Nyquist, Nyquist, 2xNyquist).

The RMK-D – Lens (Fig. 5b) was custom designed for a sensor with significantly smaller pixel size of 7.2um. The corresponding Nyquist frequency is 70LP/mm, the 50% Nyquist frequency is 35LP/mm and the 2xNyquist frequency 140LP/mm. Figure 7a) shows the modulation transfer function for discrete field points as a function of the spatial frequency. The 3 frequencies are indicated as well as the 40% contrast criteria. Figure 7b) is the other representation of the same modulation transfer function. It can be seen from the Figures that custom designing the lenses with respect to the sensor is necessary and it will not be possible to use either of the lenses with a sensor of significantly different pixel size.

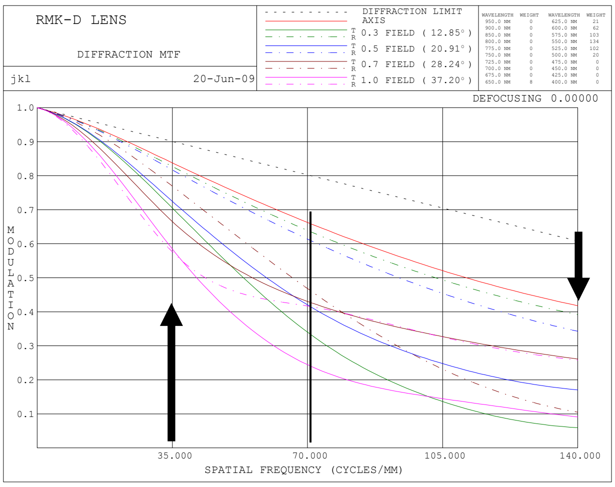

Fig. 7a: MTF as a function of υ for 6 field points for RMK-D Lens.

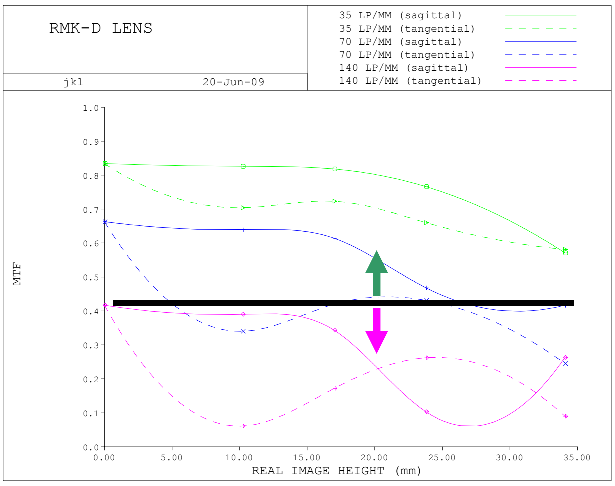

Fig. 7b: MTF as a function of field points for 3 υ (50% Nyquist, Nyquist, 2xNyquist).

A state of the art photographic lens (Fig. 5c) with similar parameters in terms of focal length, field of view and numerical aperture compared to the RMK-D lens is also analyzed.
It can be seen that even for advanced photographic lenses there are weaker requirements to the image quality at the edge of the image field compared to the center of the image field (Fig. 8b).
When considering a state of the art photographic lens within a digital sensor system, the MTF of the optical system has to be judged against the criteria for the contrast values below and above the Nyquist frequency.

If considering the photographic lens with a 12um pixel size sensor, the corresponding Nyquist frequency is 42LP/mm, the 50% Nyquist frequency is 21LP/mm and twice the Nyquist frequency is 84LP/mm. Figure 8a) shows the modulation transfer function for discrete field points as a function of the spatial frequency. The three frequencies are indicated as well as the 40% contrast criteria. Figure 8b) is a somewhat different representation of the same MTF.
The red arrows indicate potential problems: even for the modest sensor pixel size the performance at the edge of the field is not good enough. On the other hand the performance changes so much across the field that at the same time the contrast is on axis to high at twice the Nyquist frequency, indicating aliasing issues on axis.

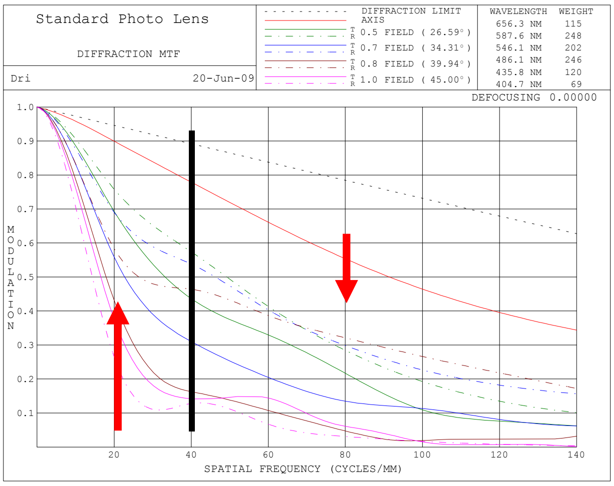

Fig. 8a: MTF as a function of υ for 6 field points for state of the art photographic lens.

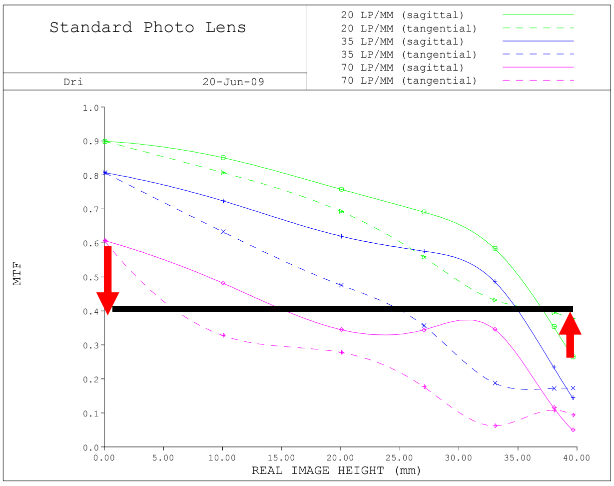

Fig. 8b: MTF as a function of field points for 3 υ (50% Nyquist, Nyquist, 2xNyquist).

From this example it can be seen, that custom designing the optical system with respect to the sensor will enable the optimum system performance. Using even state of the art photographic lenses may, without double checking the sensor limitations against the optical system limitations, cause the entire aerial system to fail or deliver results way below its theoretical potential.

3. ENVIRONMENTAL SIMULATIONS

Design and test conditions differ significantly from environmental conditions experienced on aerial survey. A temperature range in excess of +/-20°C is not unlikely to occur. Optical glasses change their refractive index as a function of temperature and also the mechanical distances change considerably. The dominant aberration is a plain defocus of the lens. This is not an issue in photographic applications, where refocusing is done manually or via an auto focus. However, lenses applied in aerial survey cameras commonly are worked in fixed focus mode due to stability and accuracy reasons. This potentially reduces the temperature range of photographic lenses within aerial survey applications by up to an order of magnitude. It leads to considerable efforts in either tempering the entire camera or actively moving lens elements according to temperature and pressure measurements [8]. At Carl Zeiss Jena, we took the approach to custom design the DMC and RMK-D lenses to be insensitive to temperature and pressure changes, therewith reducing temperature influence to a minimum. It turns out that very good designs in terms of design performance may not be appropriate designs in terms of its sensitivity to production tolerances and to the specified environmental requirements. Ideal aerial survey camera lenses are stable and

insensitive design forms achieving as-build-performance under most demanding environmental conditions.
The environmental specifications of aerial survey camera lenses challenge the optical design beyond high performance photographic lenses. Temperature ranges from -20°C up to 40°C and air pressure equivalent to flight heights up to 8000m have to be accomplished by the optical design without significant loss in performance. Within our state of the art aerial survey camera systems, due to the stringent requirements on image stability, no moving parts are allowed.

3.1. Thermal Simulations

Within the next section the three designs (DMC – PAN Lens, RMK-D Lens and Photographic Lens are compared with respect to temperature sensitivity. The performance has been evaluated in terms of the modulation transfer function at three distinct spatial frequencies. The green lines represent the contrast of meridional and sagital oriented sine patterns with a spatial frequency of 20 LP/mm. This is corresponding to 50% of the Nyquist frequency by a sensor pixel size of 12.5um. The blue lines represent the contrast of meridional and sagital oriented sine patterns with a spatial frequency of 35 LP/mm. This is corresponding to 50% of the Nyquist frequency by a sensor pixel size of 7.2um. The pink lines represent the contrast of meridional and sagital oriented sine patterns with a spatial frequency of 70 LP/mm. This is corresponding to the Nyquist frequency corresponding to a sensor pixel size of 7.2um. The contrast curves are drawn along the field positions.
There are 2 Plots for each lens, one at the design temperature of 20°C and one at the extreme temperature of -20°C (a total of 40°C temperature change). The change between the plots is a measure for the temperature sensitivity. It does not contribute for temporal temperature changes. However special care has been taken for the temperature insensitive designs. Here in addition to the overall system response, also the individual element and group responses to temperature changes are small compared to the performance measures. This is ensuring an insensitive optical design also with respect to thermal gradients.

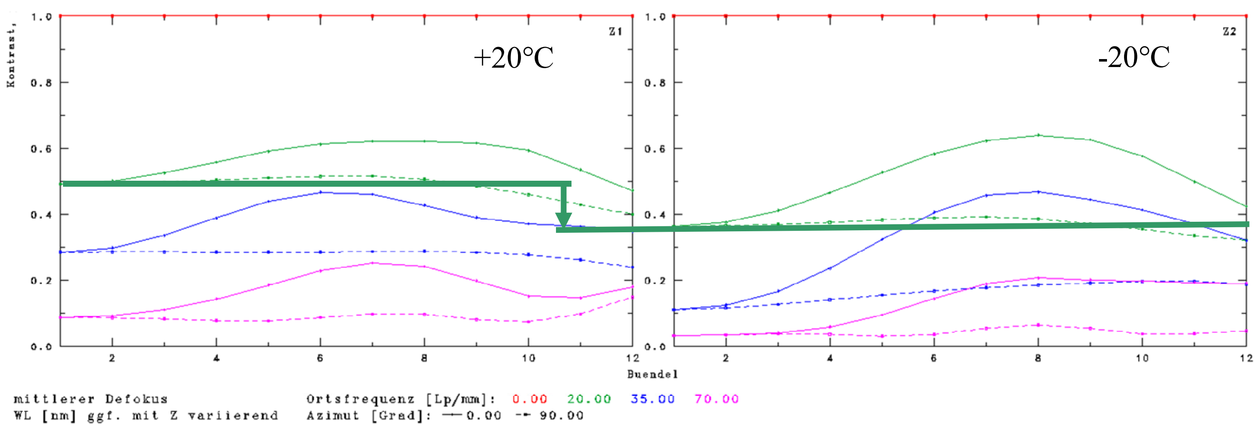

Fig. 9: MTF curves of the DMC Pan Lens at different temperatures indicating 15% MTF decrease at half the Nyquist frequency and 40K temperature change.

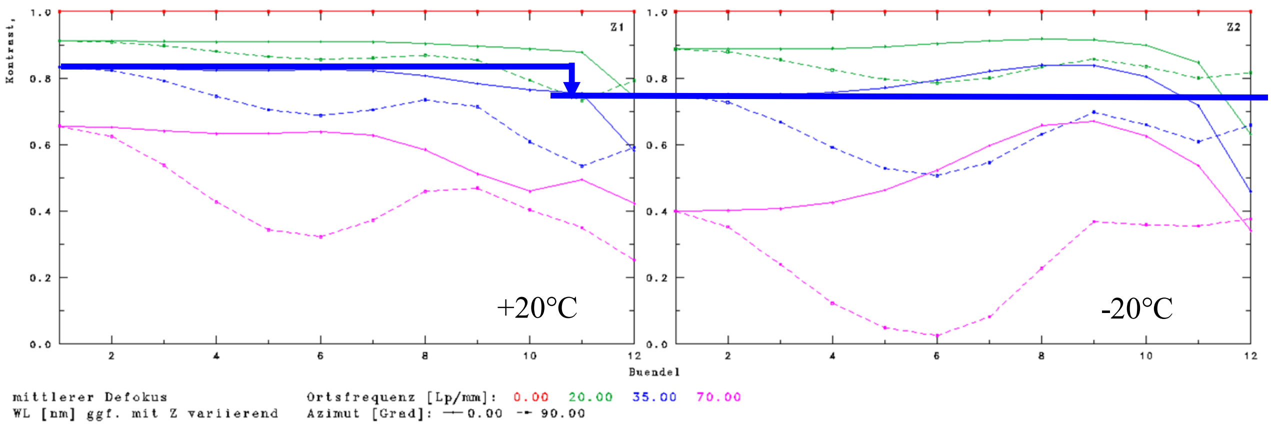

Fig. 10: MTF curves of the RMK-D Lens at different temperatures indicating 12% MTF decrease at half the Nyquist frequency and 40K temperature change.

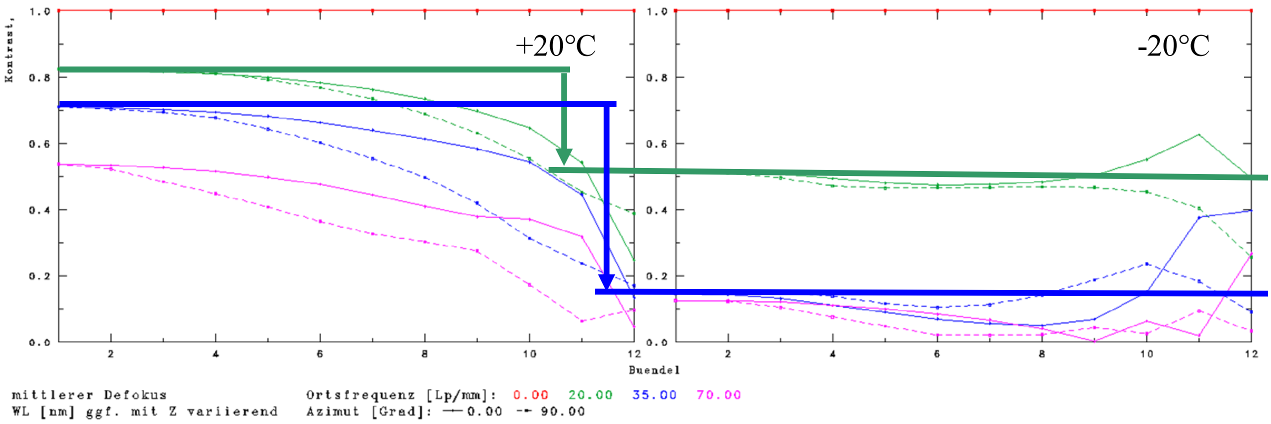

Fig. 11: MTF curves of a state-of-the-art photographic lens at different temperatures indicating 30% MTF decrease at half the Nyquist frequency of a 12um pixel sensor and 55% MTF decrease at half the Nyquist frequency of a 7.2um pixel sensor and 40K temperature change.

The DMC Pan lens experiences a 15% MTF drop at half the Nyquist frequency (Fig. 9). This compares with 12% drop of the MTF for the RMK-D MS Lens (Fig. 10). The state-of-the-art-photographic lens has been considered to be used with a significantly reduced image field with either a 12 or a 7.2um pixel sensor. Figure 11) shows MTF decreases of 30% when used with a 12um pixel sensor and 55% when used with a 7.2um pixel sensor. This again disqualifies the photographic lens for photogrammetric applications and shows the advantage if a custom designed lens.

3.2. Pressure Simulations

Similar simulations have been carried out with respect to pressure change. The designs MTF (760hPA pressure corresponding to 0m height) and the MTF at a height of 8000m are shownn. Since the field of view is different for the DMC PAN Lens compared to the other lenses, the on-axis performance change has been used as a comparison. As can be seen from Fig.12) the DMC PAN lens is very insensitive to pressure change. The performance changes by less than 5% MTF.

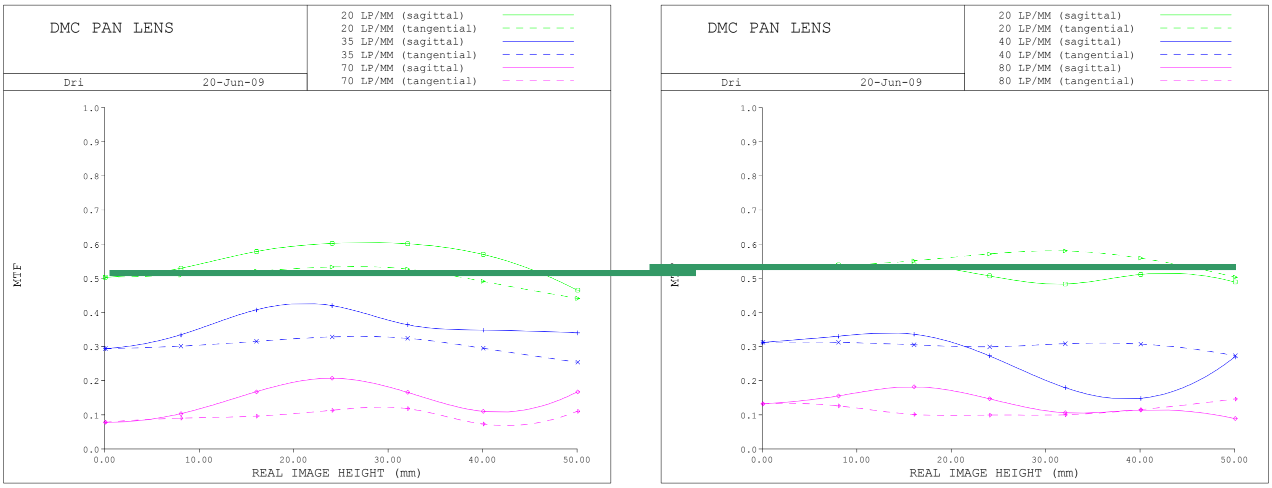

Fig. 12: MTF curves of the DMC Pan Lens at different flight heights indicating 5% MTF change at half the Nyquist frequency (green line) and 8000m height change.

The RMK-D lens is slightly more sensitive due to the smaller pixel size of the sensor Fig.13). Also at the edge of the field there occurs a slightly more pronounced drop-off in performance. This is due to the much larger field of view compared to the DMC PAN Lens. The in-axis performance degrades by less than 5% MTF over 8000m flight height change.

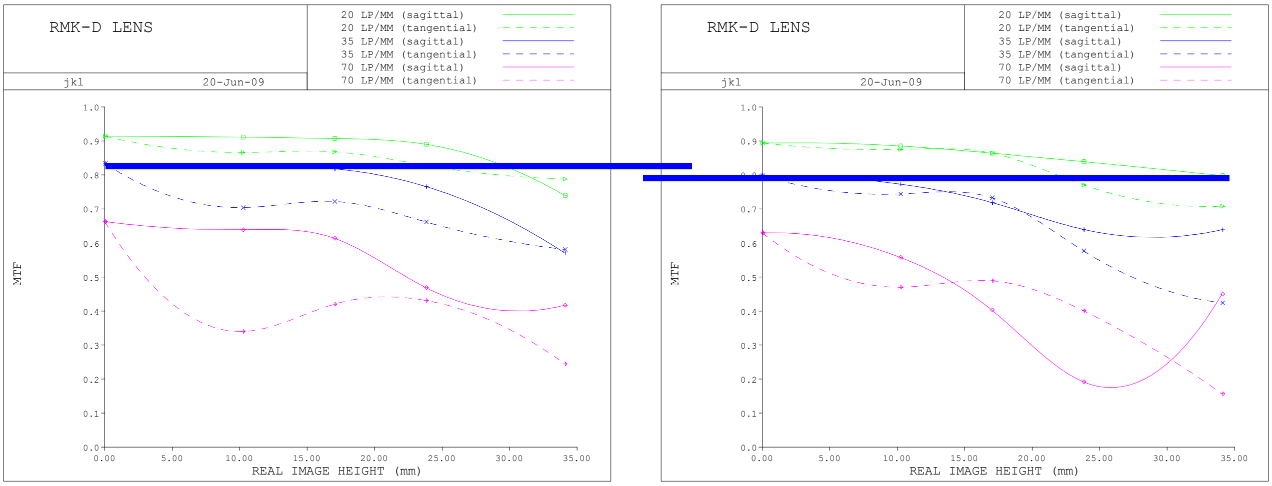

Fig. 13: MTF curves of the RMK-D Lens at different temperatures indicating 10% MTF change at half the Nyquist frequency (blue line) and 8000m height change.

The state-of the-art-photographic lens is extremely sensitive with respect to pressure change as can be seen from Fig. 14). The accuracy of this lens would change significantly with changes in pressure. This again disqualifies the photographic lens for photogrammetric applications and shows the advantage if a custom designed lens.

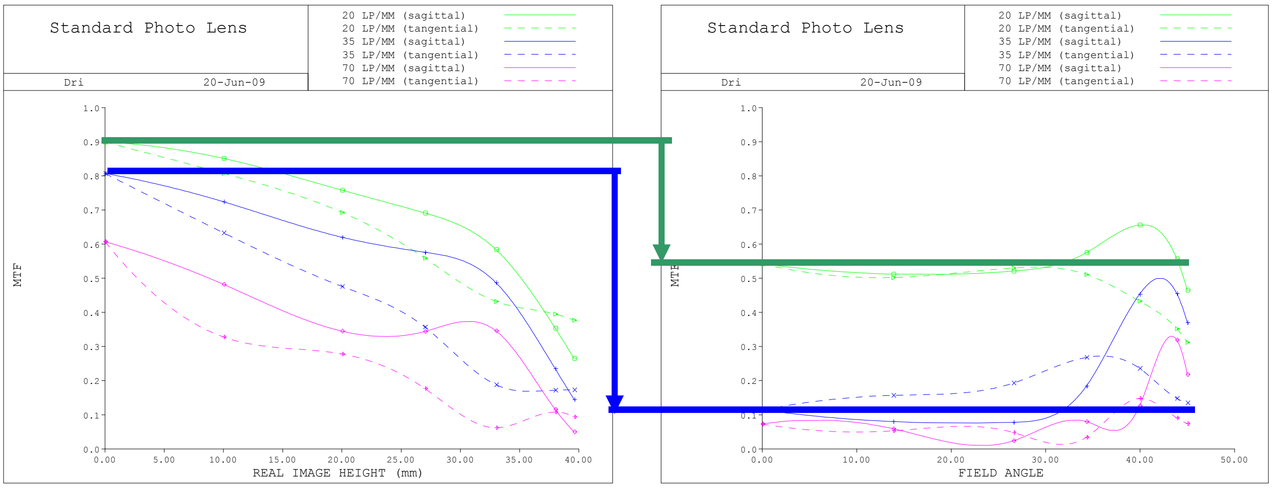

Fig. 14: MTF curves of a state-of-the art photographic lens at different temperatures indicating 25% MTF decrease at half the Nyquist frequency of a 12um pixel sensor and 60% MTF decrease at half the Nyquist frequency of a 7.2um pixel sensor and 40K temperature change.

In the digital detection age many requirements known for analogue imaging systems no longer apply. Distortion up to several percent is being correction by calibrating the lens after manufacturing. Remaining error sources are calibration errors and distortion changes of the lens due to changing environmental conditions. Again this calls for special lens designs being exceptional stable in terms of distortion variations. Without simulation results shown in this paper it is obvious, that the focus change responsible for the performance loss of the photographic lens will translate into distortion errors due to the non-telecentricity of the lens. This too will cause inaccuracies avoided by the temperature and pressure insensitive custom optical designs.

4. AS-BUILD-PERFORMANCE SIMULATIONS AND MEASURMENT DATA

In order to gain an optical system fulfilling its performance requirements, the optical design has to fulfill even harder requirements and care has to be taken, that environmental changes and tolerances take only part of the residual performance budget. A considerable part of the performance budget has to be reserved for manufacturing tolerances. The performance of an optical system with tolerances and adjustments is named as-build-performance. It can be directly compared to measured performance data after manufacturing.

For the DMC Pan Lens monte-carlo-simulations have been carried out. For a large number (100) of lenses tolerances have been randomly generated and applied to the lens design. For each lens the possible adjustments have been carried out. The resulting final systems have been analyzed with respect to the worst MTF within the entire field of view at half the Nyquist frequency and the results are visualized within a histogram (Fig. 15). It shows the distribution of as-build-performance of the simulated lenses.

The blue bars represent the on-axis MTF values, the green bars the MTF values at 0.7 x the maximum field size and the brown bars the MTF values at full field size. The abscissa shows the performance class, each bar represents an MTF range of 5%. The ordinate shows the percentage of systems within each MTF range.

From the monte-carlo-simulations it can be seen, that the DMC PAN lens has a similar performance across the entire imaging field and only a small performance variation among different systems is expected. In numbers there is a distribution of performance confined to +/- 5% MTF on-axis and only a somewhat higher variation of +/-7.5% MTF at the maximum field. For 100 systems there will be no system with an as-build-performance below 40% MTF at halve the Nyquist frequency according to the monte-carlo-simulations. From the theoretical simulations the specification on the final acceptance values for the manufactured lenses is derived and indicated as a red line in Fig. 15). The statistical analysis of measurements on a large number of lenses (100 systems) is shown in Fig. 16). The theoretical estimates on the expected spread and minimum achievable performance are impressively confirmed by those data.

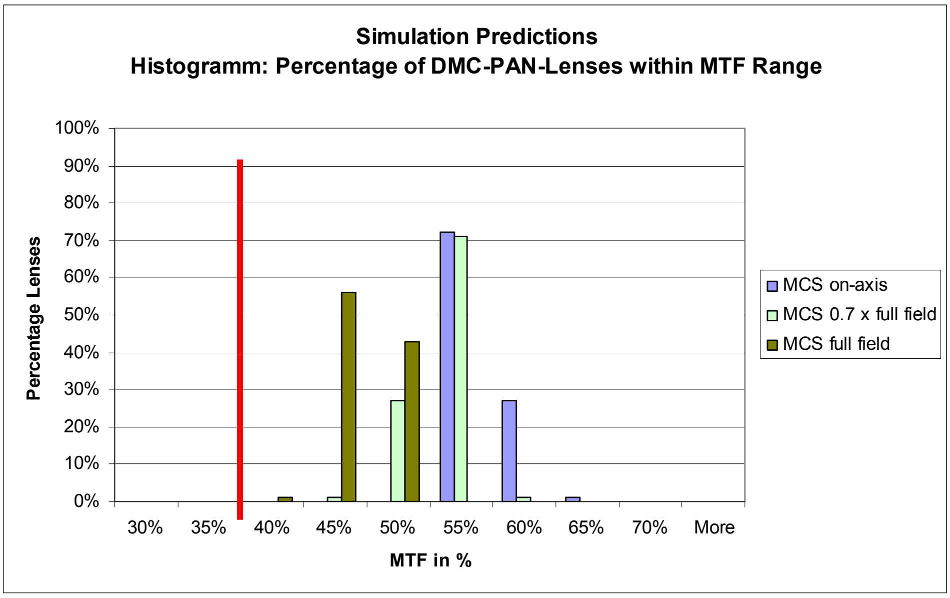

Fig. 15: Histogram simulated as-build MTF performance for DMC – PAN lens.

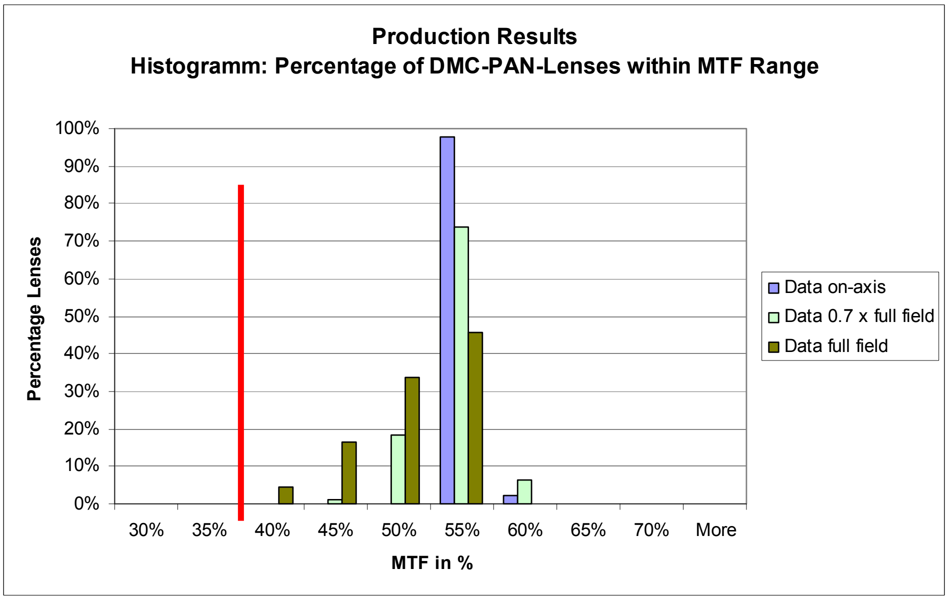

Fig. 16: Histogram of final measurement MTF performance for DMC – PAN lens.

This proves that insensitive custom optical designs together with the advanced production process at Carl Zeiss Jena deliver very deterministic and predictable performance results well within as-build-specifications for a large number of lenses (100!).

5. CONCLUSIONS AND OUTLOOK

We have shown that the performance of a state-of-the-art aerial survey camera system is driven by the pixelsizes of the sensor. For costum designed lenses it has been shown, that a match to the detector properties is necessary and achieved for the DMC and RMK-D lens, whereas a state-of-the art photographic lens comparable to the RMK-D lens would potentially have caused serious problems within the application. Thermal and pressure simulation results for a photographic lens and aerial survey lenses have been presented. It has been shown for custom designed DMC and RMK-D lensese, that a performance very close to the theoretical design performance can be achieved within the entire working environment. Wheras a state-of-the-art photographic lens being analysed, was shown to be extremely sensitive with respect to environmental changes, making it unsuitable for high performance aerial survey applications. For the DMC PAN Lens the as-buildt-performance has been shown to be very close to the theoretical design performance. We presented monte-carlo-simulations of as-build-performance data and compare them with measured performance data for a large number (100) of lenses.
It is concluded that a customized optical design ensures a uniquely stable, high performance lens that is perfectly suited for the most demanding aerial survey camera requirements.

6. ACKNOWLEDEGEMENTS

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