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...on proper lens selection

The technical term "shading" describes the light fall-off observed towards the edges of an image. When applied to a digital camera system, "shading" describes the result of various physical phenomena such as lens vignetting and the angular dependence of quantum efficiency due to the use of microlenses. This effect is particularly important when selecting suitable lenses in applications using camera systems with large image format sensors such as the Kodak KAI-11000 (4008x2672 pixel) or similar image sensors in the same pixel size and resolution range.

1 Shading

Figure 1 shows shading in images, which have been recorded with a KAI-11000 image sensor and a Nikkor 1.8/105mm lens at an f-stop f/1.8 (open aperture). The light fall-off towards the edges of the image can be clearly seen. It is even more pronounced, when the right image in figure 1 is scaled to minimum and maximum as can be seen in figure 2.

Figure 1: Both images have been recorded with a KAI-11000 image sensor and a Nikkor 1.8/105mm lens at an f-stop of f/1.8 (open aperture).
The left image shows a normal scene and the right image shows a homogeneous illuminated area. Both images are scaled to full scale, such that 0-16384 counts correspond to 0-255 gray levels.

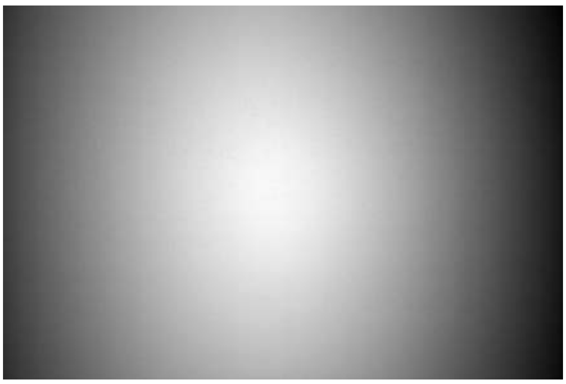

Figure 2: The image is identical to the right image in figure 1 only that the scaling is different to better illustrate the shading effect. The scaling is 5760-15743 counts correspond to 0-255 gray levels, which is a minimum/maximum scaling.

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If the aperture is closed in the same imaging situation down to an f-stop of f/8 the shading or vignetting is minimized, the reasons for that are explained in the following chapters. Figures 3 and 4 show the same images at f/8.

Figure 3: Both images have been recorded with a KAI-11000 image sensor and a Nikkor 1.8/105mm lens at an f-stop of f/8 .
The left image shows a normal scene and the right image shows a homogeneous illuminated area. Both images are scaled to full scale, such that 0-16384 counts correspond to 0-255 gray levels.

Figure 4: The image is identical to the right image in figure 3 only that the scaling is different to better illustrate the shading effect. The scaling is 9280-15519 counts correspond to 0-255 gray levels, which is a minimum/maximum scaling.

From the above images it is obvious that the shading effect is much smaller in the f/8 image. Images of the homogeneous illuminated area also show that from open aperture to f/8 the rate of fall-off or gradient of the shading changes. In figures 1 and 2 it can be seen that the gradient has a circular shape while in figure 4 for f/8 it is more horizontal. The decrease of shading can be seen from the scaling span of f/1.8 (see fig. 2: span = 17743 - 5760) 11983 and the span of f/8 (see fig. 4: span = 15519 - 9280) 6239, which is much smaller.
But what are the causes behind the shading effect and the change in its gradient?

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2 Optical Lens

One source of shading is introduced by the camera lens used to image the object onto the image sensor. Lens manufacturers refer to this characteristic as "lens vignetting", describes how outer portions of the image ray bundle are internally blocked by the inner aperture of the lens (smaller lens diameter, additional tubes). This inner aperture blocks the outer rays because their aberrations are much more difficult to correct within the lens sets and smaller lenses are easier and cheaper to manufacture. As a result, more center rays reach the image sensor as compared to outer rays. When the adjustable aperture (f-stop control) is closed down, the ray bundle becomes more restricted towards the center and the contribution of the inner aperture is minimized, resulting in minimal or no vignetting.

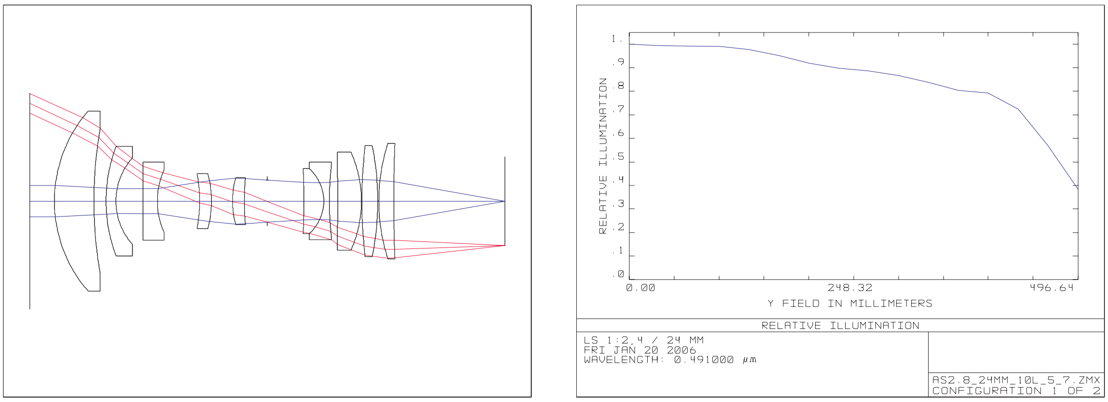

Figure 5: The left image shows a schematic of a wide angle lens set with a center or chief ray bundle (blue) and an outer ray bundle (red) which is subject to vignetting. The right image shows the result of the calculation of the relative illumination of the displayed lens set with an intensity drop of 70% at the border of the imaged area.
(schematics provided by IB/E Eckerl, www.ib-eckerl.de).

A second source is the view angle (angle-of-view) of the lens. The smaller this angle, the more “parallel” the light rays become, which are imaged through the optical system. In turn, the outer rays are less prone to the inner aperture cut off within the lens. In practical terms, the longer the focal length, the less vignetting occurs, which is illustrated in figures 6 and 7.

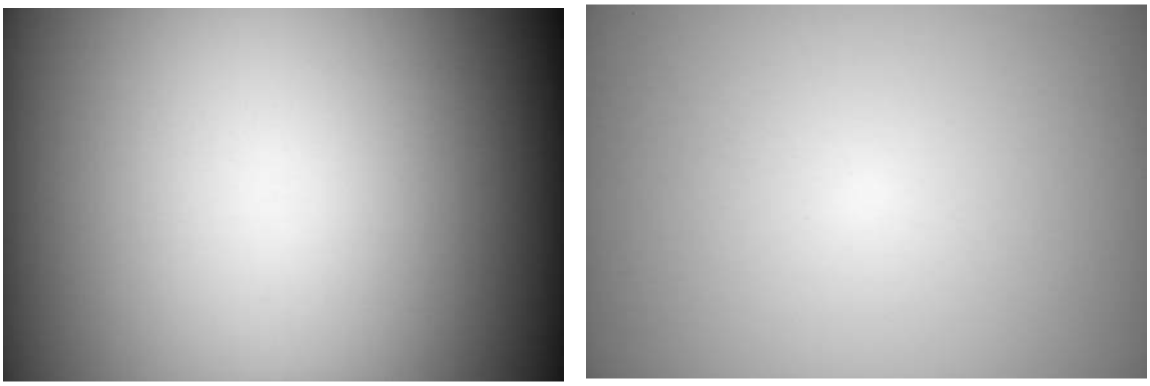

Figure 6: Both images have been recorded with a KAI-11000 image sensor .
The left image shows a homogeneous illuminated area recorded with a Nikkor 50mm at f/1.8 while the right image shows the same area recorded with a Nikkor 200mm at f/4. Both images are scaled to minimum/maximum.

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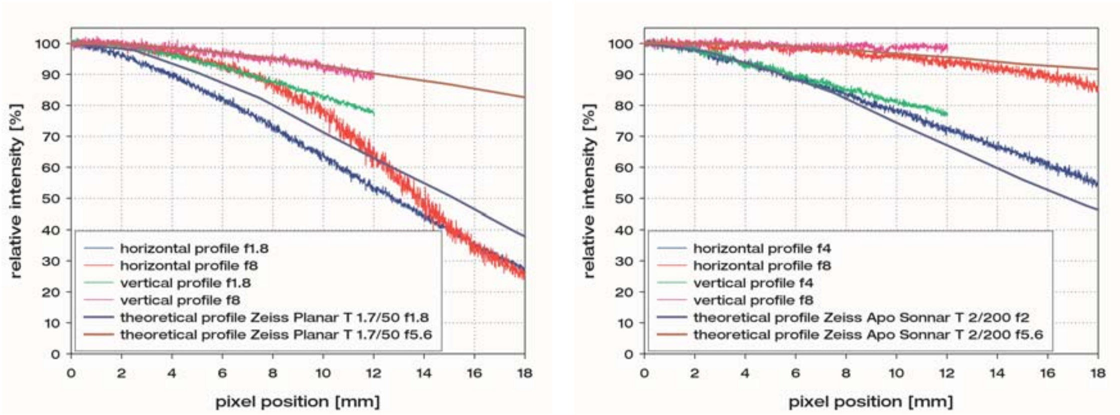

Figure 7: The graphs show a set of experimental data obtained with Nikon lenses compared to data of similar lenses of Zeiss (because only Zeiss is presenting such data in their lens product sheets).
The left graph show horizontal and vertical center profiles read out of an homogenously illuminated image with a KAI-11000 camera, which was equipped with a Nikkor 50mm f1:1.8 lens at two different f-stops: blue - horizontal f/1.8, red - horizontal f/8, green - vertical f/1.8, pink - vertical f/8, dark blue (smooth) - Zeiss 50mm f/1.7 theoretical, dark red - Zeiss 50mm f/8 theoretical.
The right graph shows the corresponding results for a Nikkor 200mm at f-stops of f/4 and f/8, and the corresponding values of a Zeiss 200mm lens.

The extracted center profiles from the images in figure 6 clearly show both of the mentioned phenomena. First, the totally open images (50mm f/1.4 and 200mm f/4) show the vignetting of 72% intensity drop for the 50mm lens and 45% intensity drop for the 200mm lens. The longer the focal length the less the shading is. Furthermore, if the aperture is closed to f/8 in both cases the shading is decreased to 70% for the 50mm and 15% for the 200mm.
It can also be seen that for 50mm the results are always worse than the theoretical value, while for 200mm the results are very similar. Also for 50mm the horizontal profiles and the vertical profiles are very different, while for 200mm they are closely matched. This can be explained by the influence of microlenses contained on the image sensors, which is discussed in the following chapter.

3 Microlenses On Image Sensors

Another source of the shading effect is introduced by the image sensors. If low fillfactor image sensors are applied, either interline transfer CCDs or CMOS sensors, usually the low fillfactor is compensated by the image sensor manufacturer with an additional layer of microlenses (see figure 8). These lenses focus the total light onto the light sensitive part of the pixel, resulting in an increase of the quantum efficiency of the sensor.

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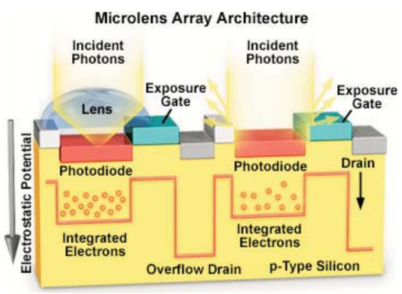


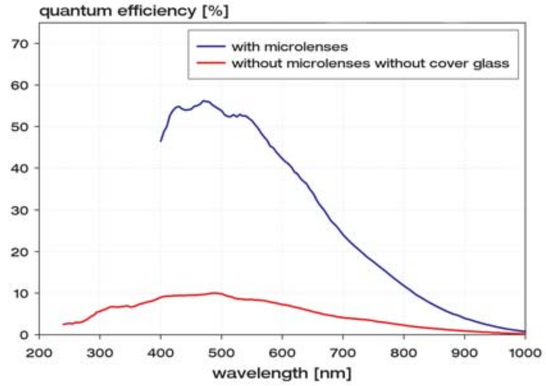
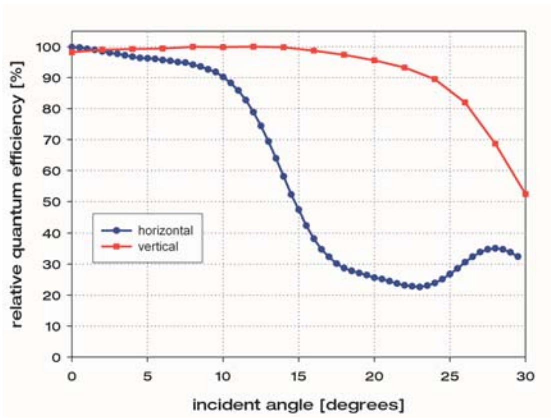


Figure 8: Left: The schematic shows a cross section through two CCD pixels. The left pixel is supplied with a microlens or lenslet, while the right pixel is not. It is shown that the light on the left pixel is focussed to the light sensitive area of the pixel, while the light falling onto the right pixel is also spread onto the gate electrodes and therefore lost to the detection.
(schematic taken from: http://www.microscopyu.com/articles/digitalimaging/ccdintro.html)
Right: Quantum efficiency measurement of a KAI-2001 interline transfer CCD with and without microlenses (data from Kodak).

The right graph in figure 8 clearly shows the benefit of applying microlenses. With microlenses the peak efficiency of the KAI-2001 is about 58% while without microlenses it is just 10% due to the small fill factor. If the pixel is thought of having a square shape and half or little less of the area is light sensitive, in many cases it results in a rectangular shape of the light sensitive area. Additionally the microlenses, as they are single lenses, do not focus properly light rays, which impinge under larger angles. This can be seen by the horizontal and vertical angular dependence of the quantum efficiency (see figure 9).

Figure 9: The graph shows the angular dependence of the horizontal (blue) and vertical (red) quantum efficiency of a Kodak KAI-11000 image sensor.



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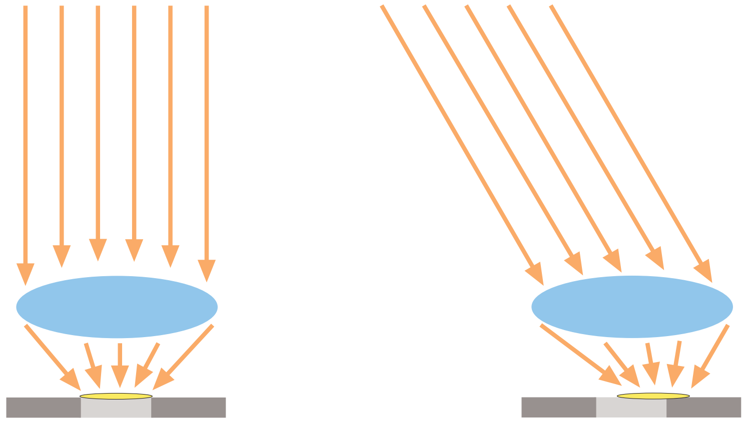
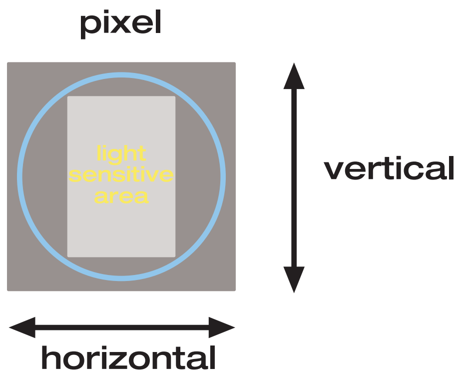


Figure 10: Schematic cross sectional view of a microlens on top of a single pixel (dark and light grey area).
Left: The lightray bundle (orange) arrives under a view angle of 0° or normal incidence (ideal conditions) at the lens and is focussed onto the light sensitive part of the pixel (light gray insert). The image light spot (yellow ellipse) matches the light sensitive part.
Right: The lightray bundle (orange) arrives under a certain view angle at the lens and is not totally focussed onto the light sensitive part of the pixel (light gray insert). The image light spot (yellow ellipse) doesn't match the light sensitive part.

The angular dependence of the quantum efficiency is caused by the geometrical distribution of the light sensitive area in a pixel and the imaging characteristics of the micro lenses. As can be seen in figure 10, if the angle of incidence of the incoming light rays fits to the imaging characteristic of the microlens, the light rays are properly focussed and hit the light sensitive area (fig. 10, left schematic). If the angle of incidence becomes larger (use of a normal or wide-angle lens, the outer optical rays) the light rays are imaged outside the sensitive area and partially hit the non sensitive part of the pixel. This results in the drop of the quantum efficiency as seen in figure 9. The difference between horizontal and vertical quantum efficiency comes from the geometrical layout of the image pixel (see figure 11). If half of the pixel of an interline transfer CCD image sensor is light sensitive, the light sensitive area stretches vertically from one border of the pixel to the other, therefore the microlens doesn't have such a large impact only for really flat angles of incidence. Horizontally the light sensitive area covers only one half of the pixel and reaches therefore much earlier the critical angle of incidence (see figure 11 the blue circle).

Figure 11: The schematic shows a single image pixel with a typical relation between total size and light sensitive area. The blue circle shows a potential micro lens.



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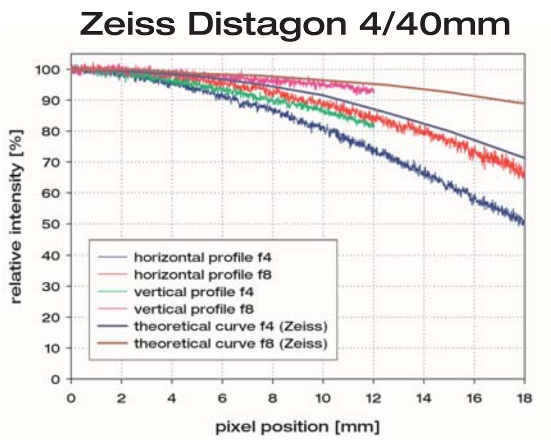
4 Reduction of Shading

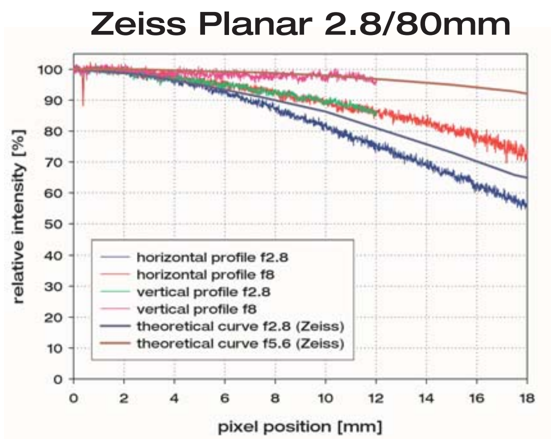
4.1 Long Focal Length and Small Aperture

The use of lenses with a long focal length at a small aperture (f/8) minimizes the shading problem dramatically as shown in figure 7 (see results with the Nikkor 200m at f/8). But for practical applications it is not a useful solution, since the use of a tele lens is not always possible and the light situation in many applications does not allow for f/8.

4.2 Larger Format Lens

These lenses were designed for imaging areas of 6cm x 6cm or 6cm x 7cm. They demonstrate similar vignetting as mentioned above, but distribute the effect over a larger area. If they are applied to f-mount type sensors, the image sensor only see the flatter part of the curve. As shown in figure 12, the experimental values of the most wide angle type of lens (the 40mm lens) show the influence of the microlenses, while for more tele type of lenses (80mm and 180mm) the drop in intensity is much less compared to the results in figure 7.





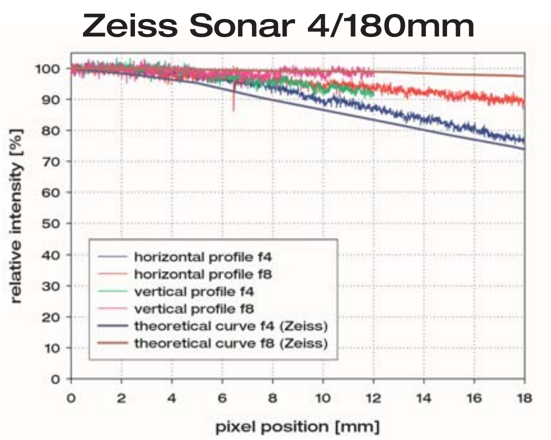


Figure 12: The graphs show a set of experimental data obtained with Hasselblad (Zeiss) lenses compared to their product sheet data.
The upper left graph show horizontal and vertical center profiles read out of an homogenously illuminated image with a KAI-11000 camera, which was equipped with Distagon 4/40mm lens at two different f-stops: blue - horizontal f/4, red - horizontal f/8, green - vertical f/4, pink - vertical f/8, dark blue (smooth) - product sheet f/4 theoretical, dark red (smooth) - product sheet f/8 theoretical.
The upper right graph shows the corresponding results for a Planar 2.8/80mm lens and the lower left graph shows the corresponding results for a Sonar 4/180mm lens at f-stops of 2.8 & 8 and 4 & 8 respectively.

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4.3 Low Shading Lenses, Optimized Lenses

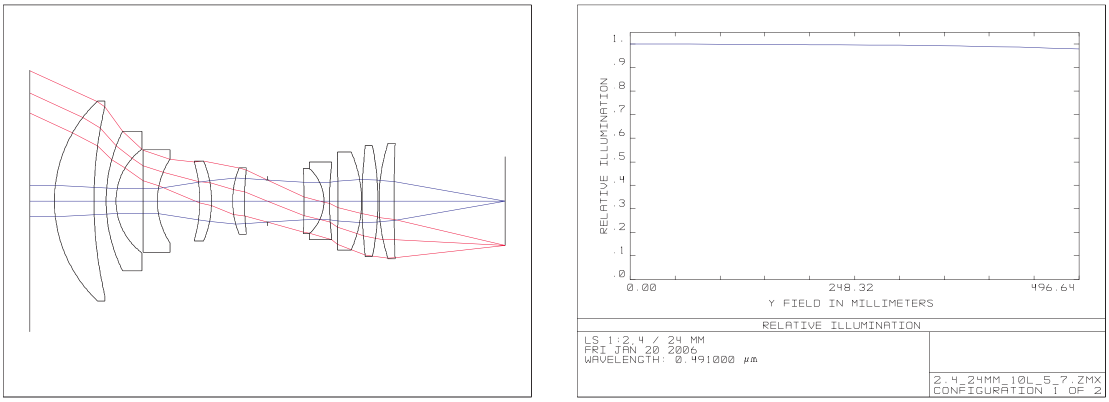

Figure 13: The left image shows a schematic of a wide angle lens set with a center or chief light ray bundle (blue) and an outer light ray bundle (red) which has minor vignetting. The right image shows the result of the calculation of the relative illumination of the displayed lens set with an intensity drop of less than 10% at the border of the imaged area. (schematics provided by IB/E Eckerl, www.ib-eckerl.de).

It is possible to create lenses that only show minor vignetting and in turn can significantly reduce the shading effect, but these lenses are typically larger, heavier and more expensive. Recently low shading optics have been released by Ingenieurbüro Eckerl (www.ib-eckerl.de) for 1" image sensors (see figure 14). Lenses for large format image sensors beyond 1" would offer the best solution to the problem, but they are currently in development and not yet available.

Figure 14: Photo of various LS "Low Shading" lenses for 1" image sensors (courtesy of IB/E, www.ib-eckerl.de).

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