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Linearization and Normalization in Spatial Frequency Response Measurement

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Abstract

The standard ISO12233:2014 describes different methods on how to measure the spatial frequency response (SFR) of an imaging system. It uses either a slanted edge (eSFR) or a harmonic Siemens star (sSFR). Within the document, it is mentioned that a linearization process shall correct a non-linear tone curve. Normalization is not further defined, but is an important part of the evaluation for the sSFR method. Using the sSFR method for texture loss analysis in the upcoming ISO19567 standard (based on a low contrast version of the Siemens star) it is even more critical. In this paper, we evaluate the influence of linearization and normalization on the results, identify issues in common implementations and present a new approach.

Intoduction

Linearization is a very typical task in image quality analysis, as all images that follow a defined out colorspace (like sRGB) have a non-linear tone response curve. Also normalization takes place in any kind of measurement, not only related to imaging. While the aim of these operations is clear, the exact process might vary between different implementations. When defining measurement procedures for international standards, these aspects do not always get the attention they should get. Therefore this paper is intended to explain some of the strategies and to show the influence this might have on the results.

SFR-Measurement

The Spatial Frequency Response (SFR) of a digital imaging system describes the ability to reproduce certain spatial frequencies. An SFR of 100% means, that the reproduction of the spatial frequency in the image has the same modulation as the modulation in the object space. So the ideal SFR equals 100% for all spatial frequencies that the system under test can reproduce. This is a range from 0 to the so called *Nyquist frequency*, which is the theoretical maximum, limited by the sampling rate of the image sensor.

The SFR is a more general term for the Modulation Transfer Function (MTF). While the SFR can be obtained in different ways, the MTF is obtained via harmonic spatial frequencies. The display and interpretation of an MTF is identical to the SFR.

ISO12233:2014

The ISO12233 standard[1] describes the resolution measurement of a digital camera. The standard describes three methods to obtain the limiting resolution, so the maximum spatial frequency that a system can resolve and two methods to obtain a SFR of the system under test.

eSFR - Slanted Edge

To obtain the eSFR, the system under test has to reproduce a slanted edge or several slanted edges to get information about dependencies of the SFR versus orientation and field position. A very common pattern is a tilted square (see Fig. 2), which instantly provides four slanted edges in two perpendicular orientations.

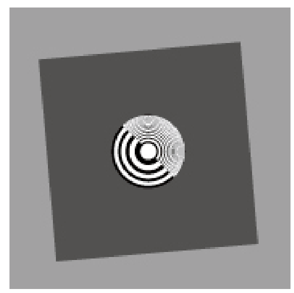

Figure 1. *A standard pattern for the eSFR measurement accorsing to ISO12233:2014; the tilted square provides four slanted edges, each of them is used to obtain a eSFR.*

The algorithm to obtain the SFR from a slanted edges uses the Edge Spread Function (ESF). This function describes how the system under test reproduces the edge, due to a binning process this can be done in a sub-pixel accuracy (typical over-sampling factor is 4). The Line Spread Function (LSF) is the first derivative of the ESF and the Fourier Transformation of the LSF makes the SFR. As an edge is used as the input signal, the SFR can be obtained for all spatial frequencies the system under test can theoretically reproduce, it is not limited by the target itself.

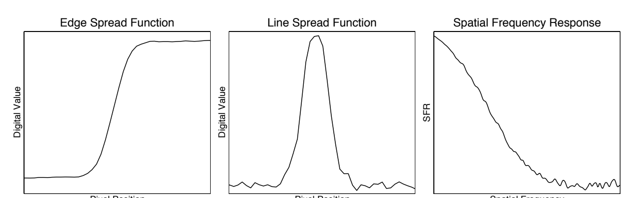

Figure 2. *Basic concept of the SFR Edge approach: The edge spread function is the over sampled intensity function of the edge. The derivative of this function is the line spread function. Transferred to the fourier spatial frequency domain, it is the spatial frequency response.*

sSFR - Siemens Star

The second method to obtain a SFR for the imaging system under test is based on a harmonic modulated Siemens star (see

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Fig. 3). The method does not use any Fourier transformation and is performed in the spatial domain only. The SFR (or MTF) for a single spatial frequency is measured by obtaining the modulation for one radius in the star. The MTF equals the measured $Modulation_{image}$ divided by the $Modulation_{target}$, so the modulation of the used test target (Eq. 1).

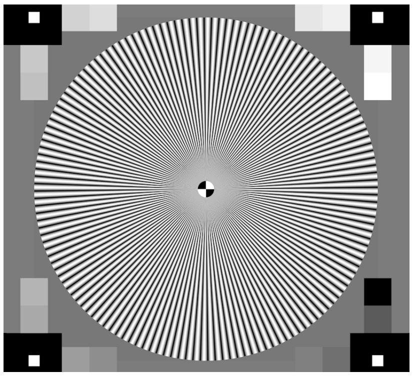

Figure 3. *The harmonic modulated Siemens star as used for the SFR measurmeent in ISO12233:2014*

$$MTF = \frac{Modulation_{image}}{Modulation_{target}} \tag{1}$$

The modulation itself is defined by Equation 2. The terms I_{max} and I_{min} represent the maximum and minimum Intensity. "Intensity" can set to "Digital Values" in this context.

$$Modulation = \frac{I_{max} - I_{Min}}{I_{max} + I_{Min}} \tag{2}$$

The frequency range of the SFR obtained using the Siemens star is limited by the size of the Siemens star. While the highest spatial frequency of the star can be chosen that way, that the resulting frequency in the image is still higher than the Nyquist frequency, the lowest frequency is limited. The lower the spatial frequency, the larger the star would have to be in the image plane. The spatial frequency in the image calculates as the number of cycles in the star divided by the circumference of a circle on this star (see Eq. 3). So it is clear, that the frequency can not go down to zero. To get information about the differences of the SFR over field, it is required to have several stars in the image. If each star covers 30% of the image height (e.g. in a 3 by 3 array of stars) and the star shows 144 periods, the lowest frequency is 153 LP/PH.

$$f = \frac{\text{Number of cylces}}{\text{Circumference}} = \frac{n}{2\pi r} \tag{3}$$

ISO19567

Next to the ISO12233 standard, another ISO standard is under development with similar methods, but different intention. The digital image processing in todays cameras is very powerful and can apply a lot of adaptive and non-linear filter to the image. Image enhancement like noise reduction can introduce a loss of low contrast, fine details. This also called "Texture loss" can not be measured with the standard targets, as these targets provide a too high contrast and do not show the effect on low contrast details.

While different structures are under discussion, one already agreed structure is a low contrast version of the Siemens star (see Fig. 4). The analyzing process is exactly the same and also the primary result is a sSFR. But especially for the low contrast version, the normalization is critical as it can have significant influence on the results at lower frequencies.

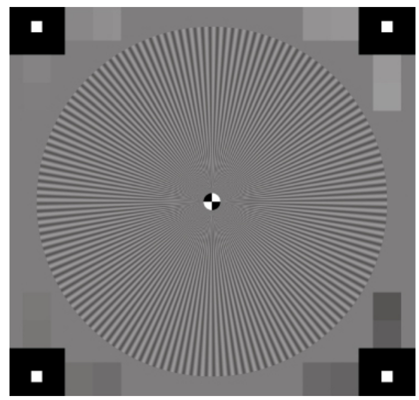

Figure 4. *The harmonic modulated Siemens with reduced contrast as proposed in upcoming ISO19567*

Non-Linearity in digital Imaging

In most cases, the sensor output data shows a linear relation between the digital value and the illumination of a single pixel. Most image processing algorithms are based on linear math, so they require linear data. For the output, the image data is converted from linear into a non-linear relation between luminance in the object space and digital values in the image space.

The top graph in Figure 5 shows the Opto Electronic Conversion Function (OECF) of a consumer cameras in RAW mode. The X-Axes shows the digital values in the Y-Channel (a weighted sum of R,G,B), the X-Axes the idealized reflection (expressed in the same range as the Y-Axes) of 16 gray patches of a Siemens star as shown in Figure 3.

Colorspace Tone Response Curve

As most consumer cameras use the sRGB colorspace, Equation 4 shows the procedure to convert from linear RGB to non-linear RGB' according to the sRGB standard. Other colorspaces might have different tone response curves, but normally have a similar shape. Note that the RGB data has to be in a range of [0...1] for these equations.

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$$
\begin{aligned}
&\text{If } R, G, B \leq 0.0031308 \\
&R'_{sRGB} = R_{sRGB} \times 12.92 \\
&G'_{sRGB} = G_{sRGB} \times 12.92 \\
&B'_{sRGB} = B_{sRGB} \times 12.92 \\
&\text{else} \\
&R'_{sRGB} = [1.055 \times R_{sRGB}]^{1/2.4} - 0.055 \\
&G'_{sRGB} = [1.055 \times G_{sRGB}]^{1/2.4} - 0.055 \\
&B'_{sRGB} = [1.055 \times B_{sRGB}]^{1/2.4} - 0.055
\end{aligned} \tag{4}
$$

The center graph in Figure 5 shows the standard tone response curve for the sRGB colorspace, applied to the same data as shown in the top graph.

Tone Curve Optimization

The tone response curve is a powerful tool to optimize the appearance of an image. The tone response curve of the output colorspace is not the only non-linear curve the device applies to the output, as it is mostly optimized for the best image appearance rather than the correct reproduction. The bottom graph in Figure 5 shows the OECF as obtained from the camera in default JPEG setting. The difference between the center and the bottom graph illustrates the optimization the camera performed and the deviation from the standard tone curve.

Linearization

The Linearization process converts non-linear image data into linear image data, so it is supposed to revert the non-linear tone curve that has been applied to the linear image data. There are different strategies to perform this task.

Invert Tone Response Curve

If the image file is encoded according to a defined colorspace, the non-linear RGB' can be converted back to linear RGB by using the tone response curve. Equation 5 is an example for the commonly used sRGB colorspace. It is the inverse function of Equation 4.

$$
\begin{aligned}
&\text{If } R', G', B' \leq 0.04045 \\
&R_{sRGB} = R'_{sRGB}/12.92 \\
&G_{sRGB} = G'_{sRGB}/12.92 \\
&B_{sRGB} = B'_{sRGB}/12.92 \\
&\text{else} \\
&R_{sRGB} = \left[\frac{R'_{sRGB} + 0.055}{1.055}\right]^{2.4} \\
&G_{sRGB} = \left[\frac{G'_{sRGB} + 0.055}{1.055}\right]^{2.4} \\
&B_{sRGB} = \left[\frac{B'_{sRGB} + 0.055}{1.055}\right]^{2.4}
\end{aligned} \tag{5}
$$

Invert OECF

As shown in section *Tone Curve Optimization*, the standard tone curve can, but does not have to be the only non-linearity that

Figure 5. *OECF (meanvalue of Y-Channel vs. idealized reflection, scaled to match image data range); measured based on linearization gray patches in a harmonic Siemens star (see Fig. 3); Constant ISO speed and f-stop, changing exposure time;* ***top****:* Y_{linear}*, extracted from camera RAW file;* ***center****:* Y_{sRGB} *standard sRGB Tone Curve applied;* ***bottom****:* Y_{sRGB} *based on JPEG output of camera*

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is applied to the image. So a perfect Linearization can not be achieved when using the fixed tone curve as defined for the used colorspace. A more precise way to linearize the image data is to obtain the OECF using defined gray patches in the target. These can be gray patches close to each measurement structure (see Fig. 3) or a single set of gray patches for several measurement structures as shown in Figure 6. For the sSFR method, it is important that the gray patches should be related to the measurement structure. The minimum and maximum reflection of the gray patches should match the range of the Siemens star.

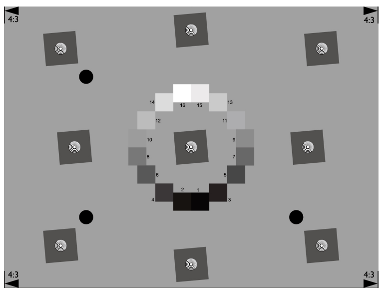

Figure 6. *The proposed chart for the eSFR measurement according to ISO12233:2014. The gray patches in the center are utilized to optain the OECF of the system under test, the tilted squares are used as measurement structures for the SFR measurement.*

To invert the OECF, the workflow is as follows:

1. Obtain the real OECF from the image data
2. Create the linear OECF based on image data and information about the gray patches
3. Interpolate a Look-Up-Table based on the real and the linear OECF
4. Apply the Look-Up-Table to the image data

The real OECF is obtained by reading the mean value of the pixel of the gray patches. The reflection of the gray patches in the target is needed to calculate the correct relation between the gray patches. The linear OECF that shall be the resulting OECF after the linearization can be created in different ways, visualized in Figure 7.

Data Range The digital value measured on the darkest patch is matched to zero, the value from the brightest patch is matches to the highest possible digital value, so digital value 255 for an 8bit image. All others are matched accordingly.

Image Range The digital values measured on the darkest and on the brightest patch remain the same, the digital values in between are matched to a line between these two points.

Normalized Image Range This is the same procedure as in "Image Range", but from the linear OECF the minimum value (obtained from the darkest patch) is subtracted. So the linear function has the same slope, but its lowest value is zero.

The *Data Range* Linearization should be avoided as it increases the contrast in the linearized image compared to the original image unless the darkest and brightest patch do not match the extrema anyways. As the dynamic range of todays cameras is larger than the dynamic range of reflective targets, this is nearly

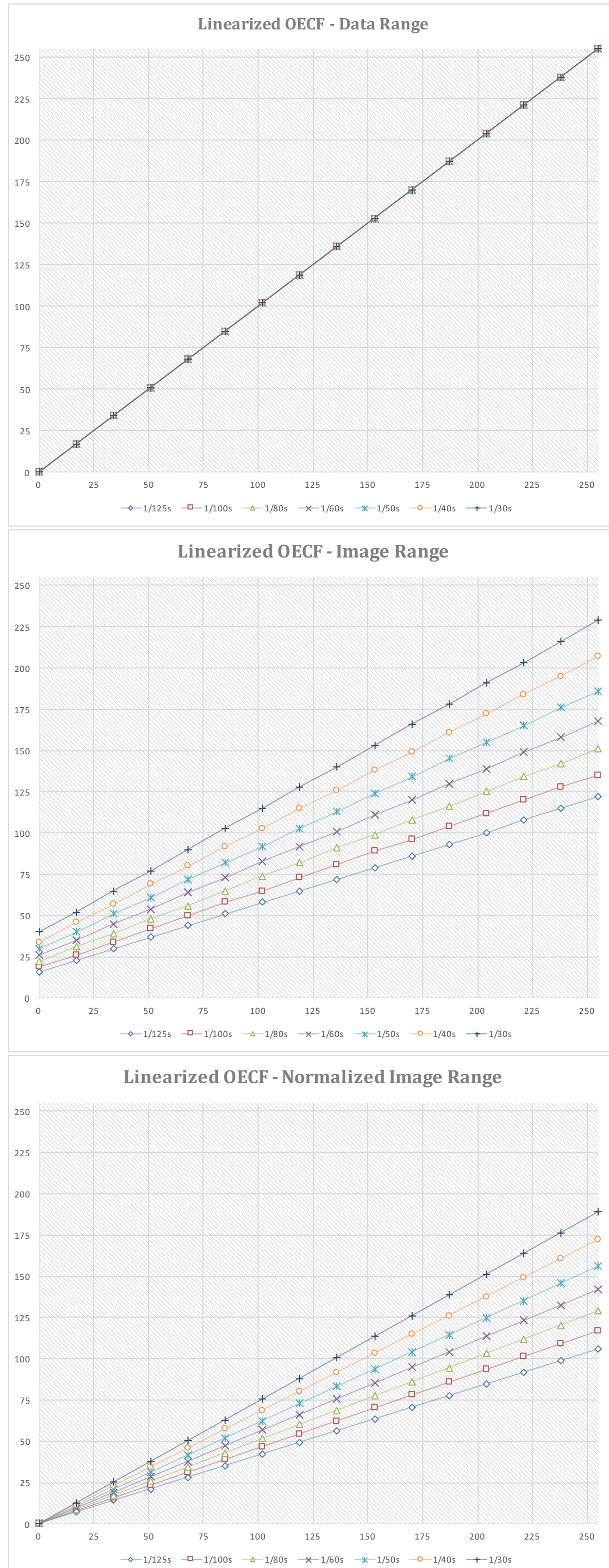

Figure 7. *Different possible linear OECF as the tagret OECF for linearization; Each plot shows the result for differentley exposed images;* ***top****: Minimum and Maximum are based on the possible data range (0...255 for 8bit)* ***center****: Minimum and Maximum are based on the measured image data* ***bottom****: Minimum and Maximum are based on the measured image data and both corrected by the measured Minimum*

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always the case. The *Image Range* Linearization is the recommended way. The subtraction of the minimum value to force the darkest patch to zero is a Normalization of the OECF and of the complete SFR. This is further explained in the section *Normalization*.

Normalization

By definition, the SFR is 100% at frequency 0. For the eSFR approach, this can easily be performed as the frequency 0 is available in the Fourier transformation of the LSF. For the sSFR method, this is more complicated for two reasons:

- The $Modulation_{target}$, so the modulation of the Siemens star is not easy to define for the camera system. As the dynamic range, the exposure and other effects have an influence on the reproduction, it can not be easily defined what the ideal modulation in the image plane would have been. As the method shall be operational for any kind of cameras with a minimum requirement of meta information about the camera system, it remains fairly unknown.
- As described in Section *SFR-Measurement*, the lowest frequency of the measured modulation can not be zero. It is not even close to zero so that this effect could be neglected. Normalizing with the lowest available frequency would potentially increase the complete SFR, especially for camera systems with a poor SFR performance where even low frequencies are well below 100%.

There are different methods to achieve the normalization for the sSFR method.

Normalize the OECF

This approach is described in the section *Linearization* as the *Normalized Image Range* definition of the target OECF. It is part of the reference implementation that has been reviewed by the workgroup of ISO12233 and has been used for different publications that describe and/or compare the results of the sSFR method. [2] [4]

When checking the Equation 2, it becomes clear that the Modulation can only reach the value of 1 if I_{min} in this equation is 0. So by subtracting the digital value found on the darkest patch, this patch gets the digital value of 0, which results in a Modulation of 100%. That way, the SFR is normalized as the modulation measured on the Siemens star will be 100% as long as the lowest values found for one frequency (radius) are zero as well.

Using this method, the digital value found on the darkest patch will become zero and all digital values lower than this will also be forced to zero in an integer image. Even though it is assumed, that the darkest patch represents the lowest digital values, this is not true for many digital camera systems that apply sharpening and/or contrast enhancement. So the Siemensstar with its fine repeated structure will show a lower minimum digital value than the darkest patch close to it. This effects results in a SFR larger 100%. When normalizing the OECF in an integer image, this contrast enhancement can not be observed, as no digital value can be lower than zero.

For the high contrast Siemens star as described in ISO12233, this is only a minor influence. But for the low contrast Siemens star as planned for ISO19567, the Normalization of the OECF has a significant influence.

Normalize with gray patch modulation

As a new approach, the normalization can be performed in a second step. So instead of including the normalization of the SFR into the linearization process, it is performed as a second step. The image data is linearized using the OECF, but the OECF is not normalized. The results of the analysis then represents the $Modulation_{image}(f)$. The $sSFR(f)$ is then calculated as

$$sSFR(f) = \frac{Modulation_{image}(f)}{Modulation_{norm}(f=0)} \quad (6)$$

The term $Modulation_{norm}(f=0)$ equals the modulation calculated based on the digital values read from the brightest patch (I_{Max}) and the darkest patch (I_{Max}).

This way a value of 100% for the SFR means, that the modulation in the star equals the modulation found between the two patches which we assume as the modulation for a spatial frequency of 0. This has basically the same effect than normalizing the OECF, but this way we include possible undershoot from sharpening and contrast enhancement algorithms and can see results of SFR larger 100%.

Results

Under- or overexposure has an influence on the SFR due to the different processing in the ISP. While the SFR is not influenced by the exposure without camera internal optimization, it does change in JPEG mode (see Fig. 8).

The eSFR results vary significantly with different linearization strategies, especially in cases where a strong sharpening is applied to the image which creates over- and undershoot along the edge as shown in Figure 9.

Figure 10 shows the influence of the different normalization on the sSFR. At lower frequencies, the difference is most present as the effects of sharpening and contrast enhancement has been applied to this image.

Conclusion

As the linearization process has an influence on the obtained SFR, it should be defined more specifically in standard documents. Especially when using the low contrast Siemens star, the differences can be significant.

The normalization is not mentioned in existing ISO standards, but it should be defined as it is a vital part of the sSFR method.

As cameras seem to process images depending on the exposure, an under- and overexposure does have influence on the measured SFR even if it still well within the dynamic range of the camera. It should be considered when designing test procedures or reviewing test results.

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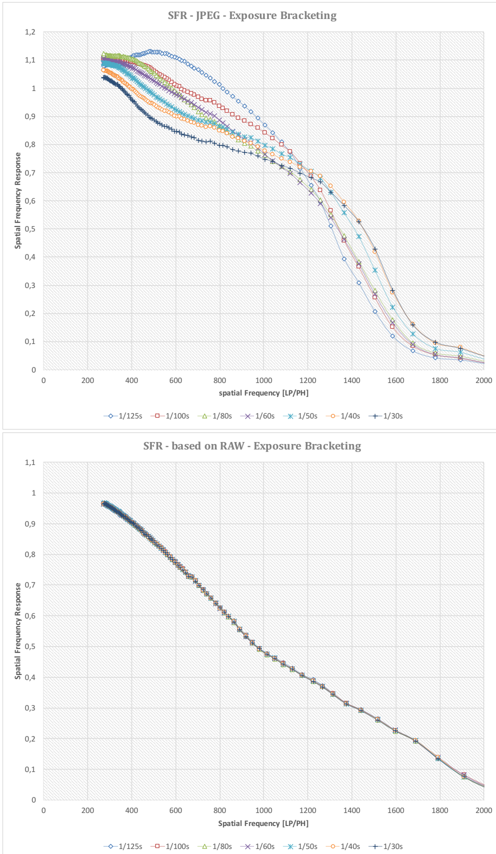

Figure 8. *sSFR (based on Siemens star) for different exposure; Canon EOS 5D MkIII; Linearization via Normalized Image Range.* ***top****: JPEG data directely from the camera* ***bottom****: TIFF based on RAW, sRGB including standard tone curve, no furter optimization*

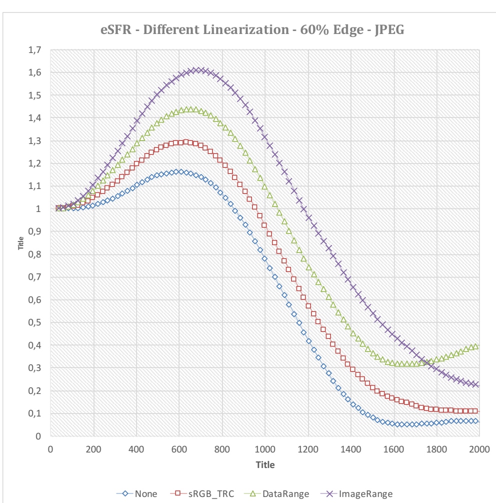

Figure 9. *The influence of different linearization strategies on the eSFR resuts; Canon 5DMkIII; JPEG sRGB data; 60% edge contrast.*

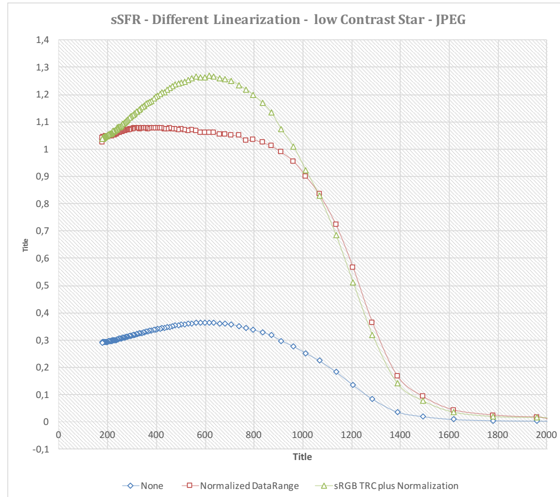

Figure 10. *The influence of different linearization and normalization strategies on the sSFR results when using a low contrast Siemens star. Without Linearization and Normalization, the SFR is very low. Normalization via the OECF does not show the sharpening in lower frequencies. Linearization via Profile with a Normalization using the GrayPatches shows the Sharpening.*

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Author Biography

Uwe Artmann studied Photo Technology at the University of Applied Sciences in Cologne following an apprenticeship as a photographer, and finished with the German 'Diploma Engineer'. He is now CTO at Image Engineering, an independent test lab for imaging devices and manufacturer of all kinds of test equipment for these devices. His special interest is the influence of noise reduction on image quality and MTF measurement in general.