Influence of camera exposure time on MTF measurements in not ideally linear systems

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1 Introduction

The theory of Modulation Transfer Function (MTF) measurements is based on the assumption of linear and shift invariant systems [1, 2, 3]. However, most experimental setups partially violate these conditions due to nonlinearities in the image detector and the discrete sampling of the image. Nonlinearities in the image detection cause a dependence of the MTF measurement results on the actual image brightness and therefore the exposure time. Thus, the MTF measurement of not ideally linear systems shows a dependence of the intensity distribution of the test target, which needs to be considered in the measurement uncertainty budget. In this contribution the multi camera MTF measurement setup at PTB [4, 5] is employed to demonstrate the influence of different exposure times on the recorded Line Spread Function (LSF) and its associated MTF.

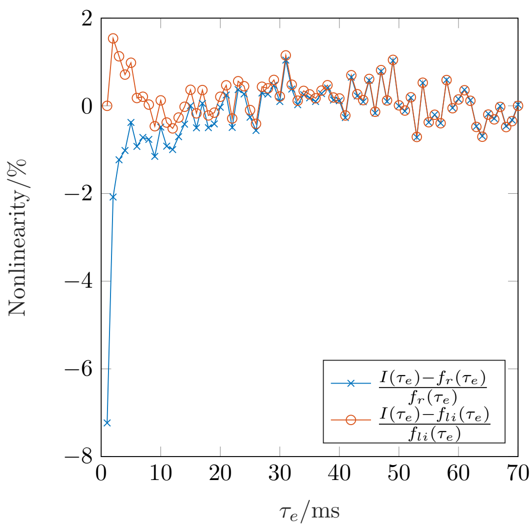

Fig. 1 *Relative deviation between the measured mean intensities $I(\tau_e)$: -and the least square regression line $f_r(\tau_e)$ (blue crosses) -and the linear interpolation between the darkest and brightest measurement f_{li} (red circles), respectively. The exposure time $\tau_e = 1\,\mathrm{ms}$ refers to a pixel saturation level of $\approx 1\%$, $\tau_e = 70\,\mathrm{ms}$ is $\approx 70\%$ saturation.*

The experiments presented are conducted employing an a2A5320-23um Basler monochrome camera with a dynamic range of 12 bit (gray value $I_{\mathrm{max}} = 4095$ at 100% saturation, $I_{\mathrm{min}} = 1$ at $\approx 0.024\%$ saturation). For this camera an EMVA data sheet [6, 7] is available. The EMVA standard defines a procedure to asses the camera sensor linearity error, by comparing the mean recorded gray values covering the $5\% - 95\%$ range of saturation to their least-squares linear regression line. In a simple test setup, we illuminate a section of the camera through a circular aperture with LED light with a center wavelength of $\approx 546\,\mathrm{nm}$. The mean number of photons per pixel is controlled by varying the exposure time in a range from $\tau_e \in [1, 70]\,\mathrm{ms}$, covering a $\approx 1\% - 70\%$ range of saturation. The mean gray values $I(\tau_e)$ are determined by averaging over 200×200 pixels in the center of the illuminated region and the nonlinearity error is determined by comparison to the least-square linear regression line $f_r(\tau_e)$ and the linear interpolation line $f_{li}(\tau_e)$ between the darkest and brightest gray value. The nonlinearity error is depicted in Fig. 1.

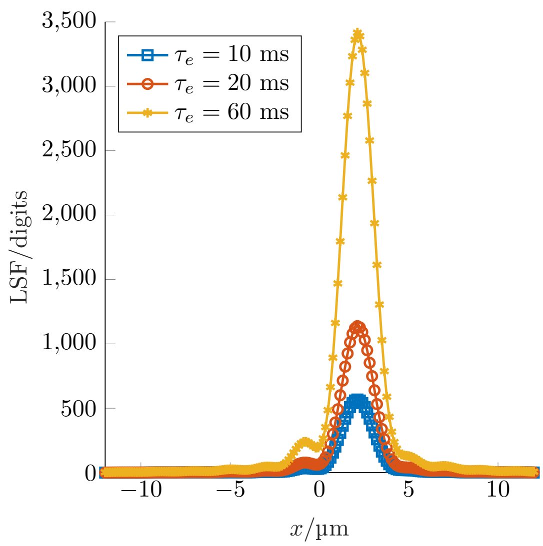

Fig. 2 *Measured LSF at exposure time $\tau_e = 10\,\mathrm{ms}$ (blue squares), $\tau_e = 20\,\mathrm{ms}$ (red circles), $\tau_e = 60\,\mathrm{ms}$ (yellow stars).*

The measured nonlinearity error is more than $10\times$ bigger than that recorded in the EMVA data sheet, which might be due to the differences in the experimental realization of the measurement. Also, the nonlinearity error increases significantly in the low saturation region $< 5\%$. It appears that sen-

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sor nonlinearities strongly influence the measurement of the LSF. Fig. 2 depicts three LSF measurements at different exposure times, recorded with the MTF measurement setup at PTB [4, 5]. The employed LSF results as the average of the LSF of many rows in the camera image and therefore features non integer values. The slit image is tilted less than $0.05°$ with respect to the pixel array allowing for the vertical averaging. For a perfectly linear detector, these LSFs should be a scaled version of each other $\mathrm{LSF}(\tau_e) = \alpha\mathrm{LSF}(\tau_{e0})$, $\alpha = \frac{\tau_e}{\tau_{e0}}$ $\forall \tau_e \in \mathbb{R}_{>0}$ and align if normalized. Here τ_{e0} refers to a fixed exposure time used as a reference.

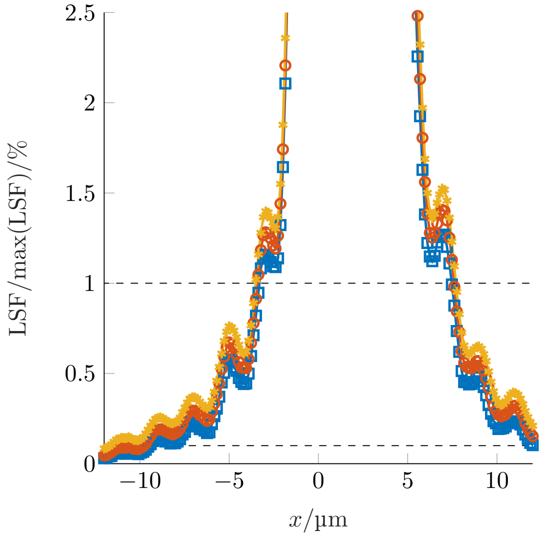

Fig. 3 *Zoomed in section of the normalized measured MTFs from Fig. 2 at exposure time $\tau_e = 10\,\mathrm{ms}$ (blue squares), $\tau_e = 20\,\mathrm{ms}$ (red circles), $\tau_e = 60\,\mathrm{ms}$ (yellow stars). A broadening of the LSF with increasing exposure time can be observed.*

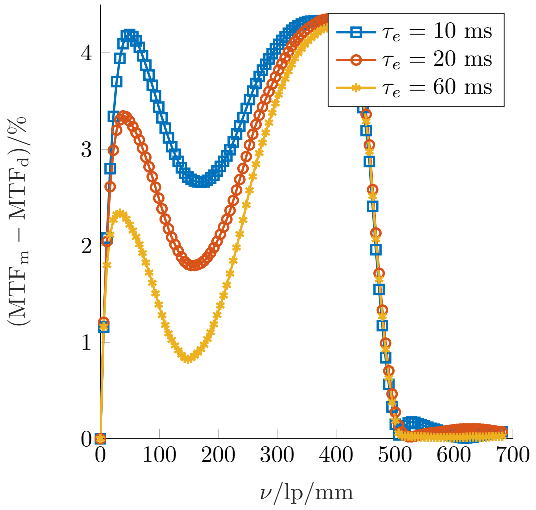

Fig. 4 *Deviation between the MTF$_m(\tau_e)$ calculated from the measured LSFs and the ideal diffraction limited MTF$_d$.*

However, as the zoomed in section of the normalized LSFs in Fig. 3 indicates, the scaling between the LSFs is not linear and a broadening of the LSF with increasing exposure time is observed. This broadening has a stronger impact for intensity values in the low saturation levels $\leq 1\%$, which also show a higher nonlinearity error. At the 1% level of the normalized LSFs, the LSF broadens by ≈ 0.5 µm when comparing $\tau_e = 10\,\mathrm{ms}$ and $\tau_e = 60\,\mathrm{ms}$ while at the 0.1% level the braodening is increased to ≈ 7.7 µm. According to the absolute LSF measurements in Fig. 2 the pixel value at the 1% level of the normalized LSFs for $\tau_{e1} = 10\,\mathrm{ms}$ is $I(\tau_{e1}) \approx 5$ associated to $\approx 0.12\%$ saturation. The small form deviations in the recorded LSF may cause MTF errors in the range of multiple percent. This is depicted in Fig. 4, where the difference of the measured MTF$_\mathrm{m}$, associated with the measured LSF from Fig. 2, to the ideal diffraction limited MTF$_\mathrm{d}$of the sample under test is compared for different exposure times.

In conclusion, the high dynamic range of the recorded LSF images required for feasible MTF reconstruction introduces the problem of nonlinearity errors. The gray values in the low saturation range $< 5\%$ show higher nonlinearity than those of well saturated pixels. If a measurement is performed at varying exposure times or with different magnifications, which change the local irradiance of the scene, the recorded LSF changes its form. This may results in MTF deviations of multiple percent. A feasible solution to consider the influence of nonlinearity errors in the measurement uncertainty is yet to be proposed.

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