Improvements for determining the modulation transfer function of charge-coupled devices by the speckle method

A. M. Pozo[1], A. Ferrero[2], M. Rubiño[1], J. Campos[2] and A. Pons[2]

[1]Departamento de Óptica, Facultad de Ciencias, Universidad de Granada, Granada 18071, Spain
ampmolin@ugr.es, mrlopez@ugr.es

[2]Instituto de Física Aplicada, Consejo Superior de Investigaciones Científicas, Madrid 28006, Spain
aferrero@ifa.cetef.csic.es, jcampos@ifa.cetef.csic.es, apons@ifa.cetef.csic.es

Abstract: We present and evaluate two corrections applicable in determining the modulation transfer function (MTF) of a charge-coupled device (CCD) by the speckle method that minimize its uncertainty: one for the low frequency region and another for the high frequency region. The correction at the low-spatial-frequency region enables attenuation of the high power-spectral-density values that arise from the field and CCD response non-uniformities. In the high-spatial-frequency region the results show that the distance between the CCD and the aperture is critical and significantly influences the MTF; a variation of 1 mm in the distance can cause a root-mean-square error in the MTF higher than 10%. We propose a simple correction that minimizes the experimental error committed in positioning the CCD and that diminishes the error to 0.43%.

OCIS codes: (040.1520) CCD, charge-coupled device; (110.4100) Modulation transfer function; (110.6150) Speckle imaging

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1. Introduction

The determination of the modulation transfer function (MTF) enables the evaluation of image quality of a system and characterizes the spatial-frequency response of an imaging system [1, 2]. One of the methods used consists of using random patterns, which can be generated in different ways: with transparency targets [3, 4], with a monitor [5] or by the generation of speckle by using a diffuser [6] or an integrating sphere [7, 8]. The main advantages of the speckle method are that the entire array is tested, it does not require a lens to project the test, and the speckle is positioned randomly in the array of pixels of the charge-coupled device (CCD).

Speckle is an interference phenomenon produced when coherent radiation is scattered from a rough surface. In the present work, we have used a transmissive diffuser to generate the speckle pattern. An aperture situated in front of the diffuser enables us to specify the content of spatial frequencies of the speckle pattern. Two of the apertures used to date have been the single-slit [6, 7] and double-slit [9]. Both present advantages and drawbacks [10]. With a double-slit, the spatial frequency interval can be extended to almost double the Nyquist frequency of the CCD, although in this case it becomes necessary to move the CCD to cover the frequency range. When a single-slit aperture is used, the MTF can be determined without the need to move the CCD, although this technique is limited by the Nyquist frequency of the device [9].

In this work, we analyse experimental factors affecting the determination of the power spectral density (PSD) from which the MTF is determined by using the speckle method with a single-slit and show that some experimental corrections can be applied to improve the MTF calculation.

First, we analysed the low-spatial-frequency region of the PSD. Boreman *et al.* [7] measured the MTF of a charge-injection device using an integrating sphere to generate the speckle. Figures 6 and 7 of their work show high values of the PSD at the low-spatial-frequency region, but they did not investigate the cause for this fact. In our work, we identified the reason for this phenomenon and show that the high values of the output power spectral density (PSD_{output}) at low spatial frequencies are due to the spatial non-uniformity in the CCD response and the non-uniformity of the field without considering the speckle. Furthermore, we show in this work that it is possible to attenuate the high values of the PSD_{output}, due to this lack of uniformity, enabling a fit of the PSD_{output} to a polynomial function. To date, the influence of a correction of non-uniformity of response of this type has not been investigated in the determination of the MTF by the speckle method.

Secondly, we have investigated how the MTF is influenced by the uncertainty in the positioning of the distance between the CCD and the aperture. In the case of the single-slit aperture, the MTF can be determined from a single measurement, but the CCD must be situated at a distance from the aperture in such a way that the maximum input spatial frequency is equal to the Nyquist frequency of the CCD [6, 7]. In this way, the MTF can be determined in the largest possible frequency range and thus aliasing is avoided. However, to date no study examines how the MTF can be affected by the experimental error in establishing the distance between the CCD and the aperture, which is an important problem since the CCD

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surface is not usually reachable because a window protects it and, consequently, it is difficult to know the distance to the aperture accurately. In the present work, we investigate this issue, analysing how the MTF is affected by small variations in the distance between the CCD and the aperture. The results show that the distance between the CCD and the aperture is critical and influences the fit of the experimental data. We propose a simple correction in the high-spatial-frequency region that enables a determination of the MTF with low uncertainty. Furthermore, by applying the correction that we propose here, the MTF is not affected by small variations in the position of the CCD with respect to the aperture.

2. Theoretical background

The MTF of the CCD can be determined from the PSDs of the speckle pattern by the expression [7]

$$PSD_{output}(\xi,\eta) = \left[MTF(\xi,\eta)\right]^2 PSD_{input}(\xi,\eta)\,, \tag{1}$$

where ξ, η are the spatial frequencies corresponding to the horizontal and vertical directions, respectively; PSD_{output} is the PSD determined from the speckle pattern captured with the CCD, and it is proportional to the squared magnitude of the Fourier transform of the speckle pattern; PSD_{input} is the theoretical PSD, known for a single slit and given by

$$PSD_{input}(\xi,\eta) = \langle I\rangle^2 \left[\delta(\xi,\eta) + \frac{(\lambda z)^2}{l_1 l_2} tri\left(\frac{\lambda z}{l_1}\xi\right) tri\left(\frac{\lambda z}{l_2}\eta\right)\right], \tag{2}$$

where $tri(X) = 1 - |X|$ for $|X| \le 1$ and zero elsewhere, $\langle I\rangle^2$ is the square of the average speckle irradiance, $\delta(\xi,\eta)$ is a delta function, l_1 and l_2 are, respectively, horizontal and vertical dimensions of the single-slit, λ is wavelength of the laser, and z is the distance between the slit and the CCD. By virtue of the geometry of the single slit, the MTF can be determined independently for the directions x and y. In the present work, we have only determined the horizontal MTF to show the corrections that we propose. This can be done in a similar way for the vertical direction.

The total MTF of the CCD can be expressed as the product of three components [11]: integration MTF (MTF_I), diffusion MTF (MTF_D), and charge transfer efficiency MTF (MTF_{CTE}), attending to the processes that originate them:

$$MTF_{TOTAL} = MTF_I\, MTF_D\, MTF_{CTE}\,. \tag{3}$$

MTF_I is a fixed modulation loss that is specific to the geometry of the pixel. MTF_D is dependent on the depth of the pixels and occurs because charge generated under a pixel diffuse to a neighbouring one. MTF_{CTE} is a consequence of the inefficiency in charge transfer from pixel to pixel. The MTF_I is given by

$$MTF_I = \frac{\sin\left(\dfrac{\pi\xi\Delta x}{2\xi_{Ny}x}\right)}{\dfrac{\pi\xi\Delta x}{2\xi_{Ny}x}}\,, \tag{4}$$

where the pixel has an open aperture of length Δx that is repeated with periodicity or pixel pitch x, ξ is the spatial frequency, and ξ_{Ny} is the Nyquist frequency of the CCD. In the CCD that we used $\Delta x = x$. The MTF measured is affected by the components MTF_I, MTF_D and MTF_{CTE}, being MTF_I the fundamental limit.

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3. Experimental device and data processing

3.1 Experimental device

Figure 1 presents the experimental device used, composed of a dye laser source tuned at 612.8 nm and emitting 100 mW, a lens to expand the laser beam (not shown in the figure), a rotating transmissive diffuser (R) to correct the response non-uniformity, a fixed transmissive diffuser (D) to generate the speckle pattern, an aperture (A), a polarizer (P) to provide a linearly polarized laser-speckle pattern, and finally a CCD detector connected to a control card installed in a personal computer. We used a single-slit aperture 1mm wide and 6mm high. For the image processing, the necessary software was developed using MATLAB.

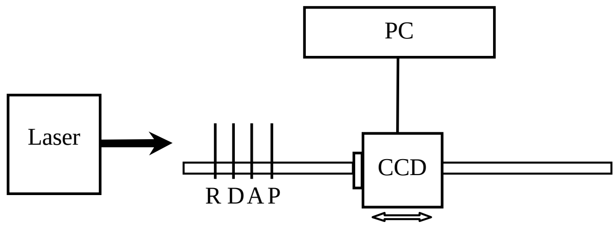

Fig. 1. Experimental set-up for the measurement of the MTF of the CCD. R is a rotating transmissive diffuser, D is a fixed transmissive diffuser, A is a single-slit aperture, P is a polarizer.

The CCD used was VGA of 640×480 pixels squared (horizontal x vertical) with a pixel pitch of 9.9 µm. The Nyquist frequency of the CCD, ξ_{Ny}, is given by $\xi_{Ny} = 1/(2x)$, 50.5 cycles/mm, in our case.

3.2 Correction at low spatial frequencies

The speckle pattern captured by the CCD imager suffers from the own spatial noise of the CCD and from the optical field non-uniformity underlying the speckle interference pattern, and both must be corrected to avoid experimental errors. With respect to the spatial noise of a CCD, a distinction can be made between the fixed pattern noise (FPN) and the photoresponse non-uniformity (PRNU). The FPN refers to the pixel-to-pixel variation that occurs when the array is in the dark—that is, it is a signal-independent noise. The PRNU is due to the difference of response of each pixel to a given signal; it is therefore a signal-dependent noise. These two types of non-uniformities have been corrected by the characterization of the CCD in use [12-15]. The FPN characterization is made by obscuring the CCD and capturing the dark image. Afterwards, the dark image is subtracted from the speckle image. The PRNU can be characterized by using a uniform irradiance field on the CCD. As the speckle does not occur with incoherent illumination, the speckle can be minimized simply by reducing sufficiently the temporal coherence or the spatial coherence [16]. In the present work, we used a technique based on the reduction of spatial coherence to minimize the speckle and to have a uniform field over the CCD. This technique consists of interposing a rotating diffuser in the path of a coherent beam to produce a random-phase modulation [17]. Figure 1 shows the situation of the rotating diffuser. The corrected speckle frame was finally derived by the expression

$$(Speckle_{corrected})_{i,j} = \frac{(Speckle_{raw})_{i,j} - (Dark)_{i,j}}{\dfrac{(Flat)_{i,j} - (Dark)_{i,j}}{\left\langle (Flat)_{i,j} - (Dark)_{i,j} \right\rangle}}, \quad (5)$$

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where $\langle \ \rangle$ indicates the mean spatial value and i,j are the coordinates of each pixel in the directions x and y, respectively. By '$Speckle_{corrected}$', we refer to the final corrected frame, '*Dark*' is the image captured with the CCD occluded and which characterizes the FPN, '$Speckle_{raw}$' is the image taken with the rotating diffuser stopped, and '*Flat*' is the frame captured with the rotating diffuser in movement which jointly characterizes the PRNU and the non-uniformity produced by the slit.

To reduce the temporal noise [18], we averaged the speckle_{raw} images and flat images over 400 frames, while the dark images were averaged over 100 frames only since their noise is lower. For the measurements, we used an integration time of 10 ms for the CCD. Section 4 presents the differences found between the corrected and uncorrected PSD_{output}.

Once the corrected speckle frame is obtained, we calculate the squared magnitude of the Fourier transform of each row of the frame by the fast Fourier transform algorithm. The result was averaged over all the rows of the speckle pattern to reduce even more the temporal noise [18]. In this way, the PSD_{output} is determined. Finally, applying Eqs. (1-2), it is possible to determine the MTF of the CCD.

3.3 Correction at high spatial frequencies

The problem of correctly determining the MTF by the single-slit speckle method is rooted in situating the CCD at the appropriate distance with respect to the aperture so that the maximum spatial frequency contained in the speckle pattern is equal to the Nyquist frequency of the CCD. The distance z between the CCD and the aperture can be calculated by the expression

$$z = \frac{l_1}{\lambda \xi_{Ny}}, \tag{6}$$

where l_1 is the slit width, λ the wavelength of the laser, and ξ_{Ny} the Nyquist frequency of the CCD. In our case, we get z = 32.3 mm. This value of z really corresponds to the distance between the slit and the CCD plane where the pixels are found. However, the surface of the pixels is not accessible because it is protected by a window. Besides, neither the distance from the window to the surface, neither the thickness of the window and its refractive index are known. Therefore, it is difficult to place the CCD at exactly the correct distance from the aperture, this being the cause of a systematic error in the high-frequency range of the PSD_{output}. Studying this error, we have placed the external face of the protective window at distance slightly shorter than z from the aperture and have measured the PSD_{output} at this distance and another around it. It is worth remarking that, for the CCD under study, the protective window is very close to the surface of the pixels.

In the following section, we show the influence exerted on the MTF by small variations in the position of the CCD with respect to the slit, and the results found with the correction that we propose, which consists of subtracting the baseline level in the fit of the PSD_{output}.

4. Results and discussion

In Fig. 2(a), the PSD_{output} determined for the speckle pattern without correcting the response non-uniformity is shown against the spatial frequency normalized to the Nyquist frequency. It bears noting the high values obtained at low spatial frequencies for the PSD_{output} that impede to fit a low order polynomial to the experimental data. These high values are found below the normalized frequency 0.0125, which is equivalent to 0.63 cycles/mm.

Figure 2(b) shows the PSD_{output} on applying the correction of the response non-uniformity [Eq. (5)] to the speckle pattern. Comparing Figs. 2(a) and 2(b), we do not get high PSD_{output} values at low frequencies when the correction of the response non-uniformity is used.

To investigate the influence in the PSD_{output} of varying the distance between the CCD and the slit, we measured the PSD_{output} at 3 different distances between the window of the CCD and the aperture. The first distance chosen between the window and the aperture was 31.8 mm, very close to the value of z obtained from Eq. (6) for the CCD under study. Figure 3

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provides a representation of the replicated PSD_{output} which clearly shows the aliasing. For this distance, the Nyquist frequency is still not reached because the overlap has still not occurred, and therefore the cut-off frequency of the PSD_{output} is lower than the Nyquist frequency of the CCD. It would thus be necessary to further reduce the distance between the CCD and the aperture and because of that two more measurements were done at 30.8 mm and 29.8 mm.

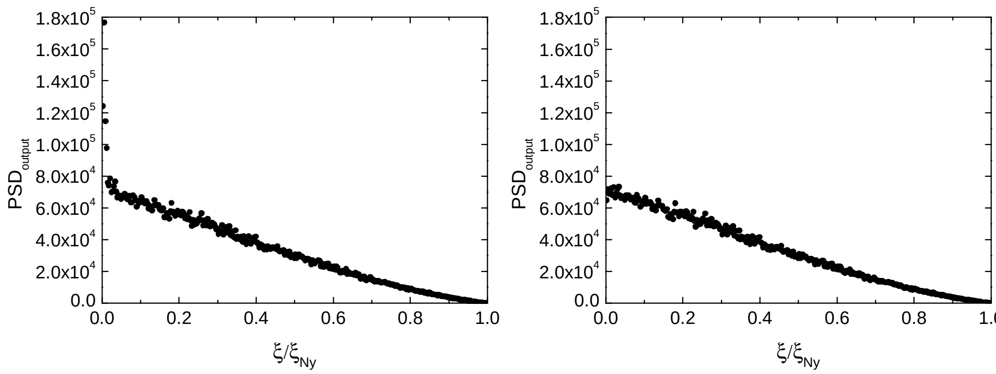

Fig. 2. PSDs determined for a distance of 30.8 mm between the window of the CCD and the single-slit aperture (a) without correction of response non-uniformity and (b) with correction. On the abscissa axis, the spatial frequency is normalized to the Nyquist frequency of the CCD (50.5 cycles/mm).

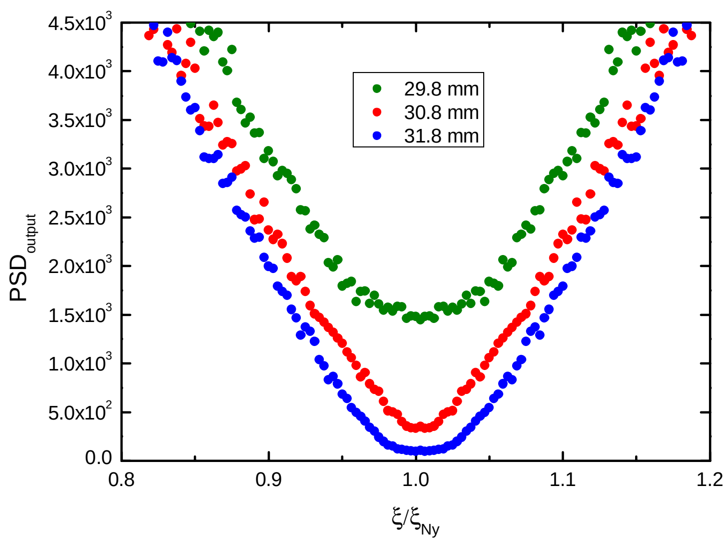

Fig. 3. Detail of PSDs found at three different distances between the window of the CCD and the single-slit aperture. Represented on the abscissa axis is the spatial frequency normalized to the Nyquist frequency of the CCD.

Figure 3 shows that as the distance between the CCD and the slit diminishes, the minimum of the PSD_{output} begins to increase due to the overlap of the two branches of the spectrum. The correction that we propose here consists of subtracting this minimum value (corresponding to the Nyquist frequency) that can be considered as a baseline value, to the fitted curve of the PSD_{output}. This subtraction should be done when the overlap of the two branches begins.

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Once the speckle frame is corrected by Eq. (5), we get the MTF from the PSD_{output}, following the procedure of Boreman *et al*. [7]. The PSDs corresponding to 29.8 , 30.8 and 31.8 mm fit to third-order polynomials with correlation coefficients of 0.995, 0.996, and 0.995, respectively. After this, it suffices to use Eqs. (1-2) to calculate the MTF (Fig. 4). This figure reveals that different curves result for the different CCD positions. To quantify the deviation between the curves, we calculated the root mean square (rms) error. The rms between the MTF at 29.8 mm and the MTF at 30.8 mm was 10.6%, between the MTF at 29.8 mm and MTF at 31.8 mm it was 16.0% and the rms error between MTF at 30.8 mm and MTF at 31.8 mm was 5.6%.

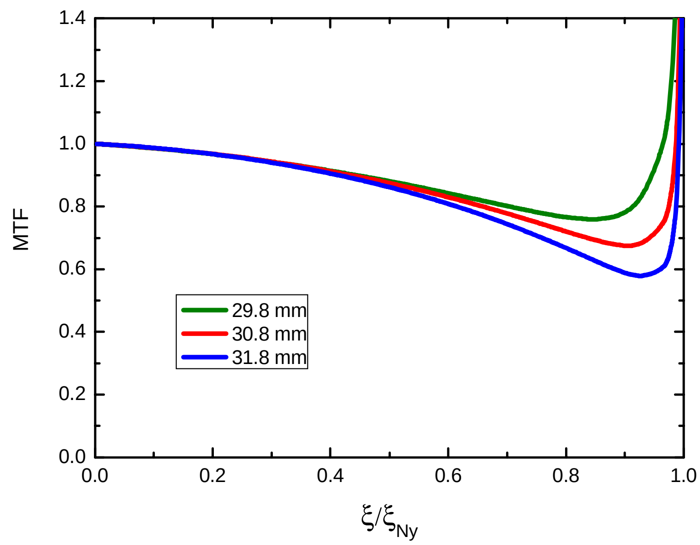

Fig. 4. MTFs of the CCD determined from the PSDs shown in Fig. 3. On the abscissa axis, the spatial frequency is normalized to the Nyquist frequency of the CCD.

As mentioned above, the correction that we propose consists of subtracting the baseline value (corresponding to the Nyquist frequency) in the fitted PSDs once the overlapping begins in the replicated PSD_{output}. Figure 5 shows the MTFs calculated after applying correction for the distances of 29.8 mm and 30.8 mm, and the MTF calculated for 31.8 mm are compared. We can see how both MTFs are much closer now than before correcting them. The rms error between the corrected MTFs is only 0.43%, while without correction it was 10.6%. In view of these results, we conclude that the correction proposed minimizes the influence of the error committed on positioning the CCD with respect to the aperture. In addition, this correction presents the advantage that eliminates the growing part in the MTF near the Nyquist frequency (compare Figs. 4 and 5) and therefore permits the characterization of the CCD up to the Nyquist frequency.

It is important to note that the objective of the correction proposed here is not to remove nor to analyse the aliasing of the speckle pattern, but rather to minimize the influence of the aliasing in the measurement of the MTF. The influence of the aliasing in the PSD_{output} depends on the method used to measure the MTF, since the PSD_{output} depends on the pattern used as the input signal. In our case, as shown in Fig. 3, the main effect that the aliasing causes in the PSD_{output} due to the error committed experimentally on positioning the CCD is equivalent to an increase in the baseline level. In effect, on diminishing the distance between the CCD and the aperture, the speckle pattern contains frequencies higher than the Nyquist frequency, which are aliased to lower frequencies. Because of this, the baseline level of the

PSD_{output} increases. The results shown in Fig. 4 confirm experimentally that the increase in the baseline level due to the aliasing is the main cause of the dispersion of the MTF values at high frequencies. By applying the correction that we propose here, the MTF is not affected by small variations in the position of the CCD with respect to the aperture, as shown in Fig. 5. This does not mean that the aliasing of the speckle pattern has been removed on applying this correction, but rather that the influence of the aliasing has been minimized in order to measure the MTF with low uncertainty.

Figure 5 also presents the integration MTF. All MTFs determined experimentally were found below the MTF_I, as was necessary, given that the MTF_I sets the theoretical limit for MTF performance. The differences between the experimental MTFs and the MTF_I were due to the components MTF_D and MTF_{CTE} of Eq. (3). It might be expected for MTF_D to be noticeable in this CCD, since pixels are small and charge may diffuse to neighboring pixels. It might also be expected for the MTF_{CTE} to be noticeable, since the CCD has a large number of pixels and there are many charge transfers involved.

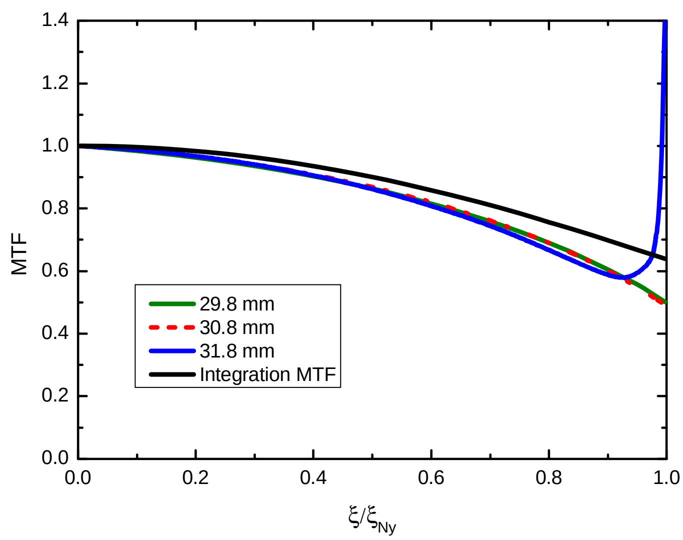

Fig. 5. MTFs for distances of 29.8 mm and 30.8 mm between the window of the CCD and the aperture determined after applying the correction of the baseline value. Also represented is the MTF (without correction) for a distance of 31.8 mm between the window of the CCD and the aperture. Integration MTF sets the theoretical limit for MTF performance. On the abscissa axis the spatial frequency normalized to the Nyquist frequency of the CCD is represented.

5. Conclusions

In this work, we analysed experimental factors affecting the determination of the PSD from which the MTF is determined by using the speckle method with a single-slit. Furthermore, we have proposed two improvements of the method of measuring the MTF of CCDs by speckle patterns. First, we analysed the low spatial frequencies. We showed that the high values of the PSD_{output} are due to a non-uniformity of response. By correcting the non-uniformity of the response the PSD_{output} peak at low frequency disappears and a low order polynomial can be fitted to the PSD_{output} to calculate the MTF. Secondly, we have analysed the region of high spatial frequencies. Our results show that the distance between the CCD and the aperture is critical. The imprecision in experimentally establishing the distance between the CCD and the aperture influences the fit of the MTF. A slight variation (on the order of 1 mm) in the position of the CCD with respect to the aperture causes a root-mean-square error of 10.6%

between MTFs. After a simple correction consisting of subtracting the baseline level in the fitted PSD_{output}, the root-mean-squared error between MTFs determined at different positions is reduced up to 0.43%. This correction minimizes therefore the influence of the error committed experimentally on positioning the CCD with respect to the aperture, and permits furthermore to characterize the CCD up to the Nyquist frequency. These two corrections should be taken into account when determining the MTF of CCDs by the single-slit speckle method with low uncertainty.

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