J. Eur. Opt. Society-Rapid Publ. 2025, **21**, 20
© The Author(s), published by EDP Sciences, 2025
https://doi.org/10.1051/jeos/2025012
Available online at: https://jeos.edpsciences.org

EOSAM 2024
Guest editors: Luca De Stefano and Raffaele Velotta

Journal of the European Optical Society-Rapid Publications

RESEARCH ARTICLE

OPEN ACCESS

Influence of ambient temperature changes on the focus point for measurements of the modulation transfer function MTF

Hanno Dierke* and Markus Schake

Physikalisch-Technische Bundesanstalt PTB, Bundesallee 100, 38116 Braunschweig, Germany

Received 24 January 2025 / Accepted 19 March 2025

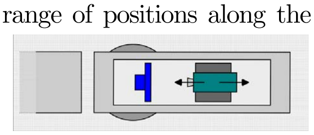
Abstract. At Physikalisch-Technische Bundesanstalt (PTB), a multi camera measurement setup is developed for the traceable determination of the modulation transfer function (MTF) of objectives. In recent works the MTF of a reference objective is determined within the image field in an angular range of up to ±20° to the optical axis. For the investigation of angular dependence of the transfer function, the MTF for a given spatial frequency is evaluated at a datum point. A common choice of the datum point is the focus point P_f. There are different methods to obtain the focus point from the measurement data. In this contribution several approaches for the determination of the focus point are investigated and compared. In addition, owing to the temperature dependent extension of the measurement setup the position of the focus point strongly depends on the ambient temperature. We also present some results of investigations on the influence of temperature changes on the position of the focus point.

Keywords: Modulation Transfer Function, MTF, Focus point, Ambient temperature.

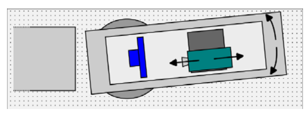
1 Introduction

The modulation transfer function (MTF) is a parameter commonly used to characterize the imaging properties of optical elements [1, 2]. The MTF contains information about the resolution as well as the ability of the optical element to transfer the object contrast into the image space. In addition, the MTF can be calculated on the basis of the design parameters, so that deviations from the calculated MTF provide an indication of existing imaging errors. At the Physikalisch-Technische Bundesanstalt (PTB), a measuring device for the traceable determination of the MTF in the image field (field angle currently $\theta = \pm 20°$) is being set up based on a method proposed in ISO9335 [3–5] (Fig. 1). The following measurement modes can be used:

- Measurement of the MTF in a fixed position for a range of spatial frequencies.
- Measurement of the MTF for a selected spatial frequency in a range of positions along the optical axis z.



This mode will be referred to as "(through) focus scan", as the measurement range usually includes the so called focus point P_f, which characterizes the position at which the MTF reaches its maximum value for a certain spatial frequency and when measuring along the optical axis (field angle $\theta_R = 0°$).
- Measurement of the MTF in a range of positions along a rotated axis z' leading to several focus scans in the image field of the sample under test ("field scan").



A reference position is required in particular to determine the angular dependence of the MTF and to compare measurements. Usually, the focus point P_f mentioned above is used. After assessing different approaches on the reliable determination of the focus point from the measurement data [6, 7] and the influence of the employed camera [5, 8] this contribution is about the influence of changes in the ambient temperature on the measured position of the focus point P_f owing to the thermal expansion of the measurement setup components.

2 Determination of the focus point P_f

Previously, the focus point was determined by simply using the z coordinate of the data point with the highest MTF

* Corresponding author: hanno.dierke@ptb.de

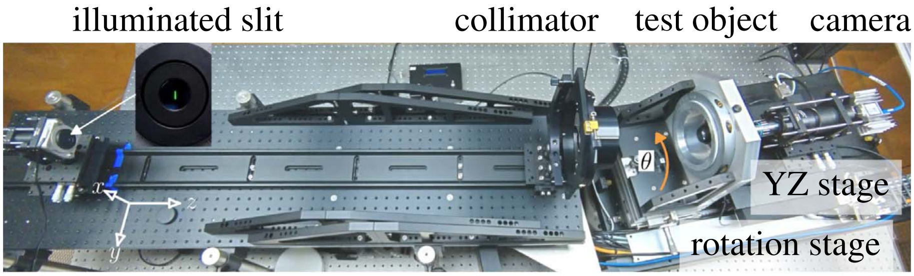


Figure 1. MTF measurement setup.

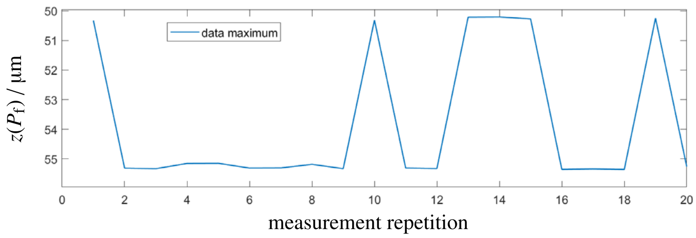


Figure 2. Focus point position $z(P_\mathrm{f})$ determined from the measurement data maximum, focus scan with d_m = 5 µm pitch, 20 repetitions [6].

value as the focus point position $z(P_\mathrm{f})$. This was quite robust as it is present in almost every data set. But the maximum value is strongly influenced, for example, by noise and thus prone to focus point deviations that directly correlate with the focus scan step width Δz ($c_{P_{f,\text{data max}}} = \pm\frac{1}{2}\Delta z$).

This is clearly visible in Figure 2 where the results obtained from repeated focus scans at the same position are shown. The focus point position determined using the maximum MTF data value results in basically two different locations that are approximately 5 µm apart (i.e. the applied focus scan step width). However, this also means that minor changes in the measurement conditions like the ambient temperature or camera temperature (cf. [5]) are not recognised as long as they do not result in the data maximum being reached at a different measurement value.

In measurements presented in [6] on obtaining the focus point more precisely polynomial fits were used and a 4th degree polynomial was proposed to be used for the determination of the focus point location $z(P_\mathrm{f})$ (cf. Fig. 3). In that contribution the use of higher order fits appeared to be less robust and did not result in a significant reduction of the fit residuals.

Recent investigations though show that using a 6th degree polynomial for the focus point fit is preferable, as the residuals could be further reduced and the robustness of the polynomial fit could be significantly improved by more suitable boundary conditions for the fit maximum. The focus point position $z(P_\mathrm{f})$ is obtained using the roots of the fit polynomials first derivative, if one of the roots is within the measurement range, is non-complex, and the second derivative of the fit polynomial at that position is negative.

3 Temperature dependence of the focus point P_f

Another question regarding the focus point is how it is affected by temperature variations and how the temperature dependence of the focus point position influences the determined MTF value of the test object. To investigate the influence of temperature changes repeated focus scans have been performed. The orientation of a slit target imaged by the measurement system was changed from tangential to sagittal and vice versa between consecutive focus scans. Since the line spread function (LSF) of the sample under test is determined from the camera image (cf. Fig. 4), the image coordinate of the LSF maximum represents the position of the target image on the camera sensor. Deviations in the maximum position hint towards a motion of the measurement setup perpendicular to the optical axis, either in horizontal (obtained from the measurements with tangential/vertical target orientation) or vertical direction (from measurements with sagittal/horizontal target orientation).

While the influence of the camera temperature during warm-up has been shown in [5], in the investigations presented here the ambient temperature was changed during repeated through focus scans and the influence on the LSF maximum and the focus point position representing the x/y and z shift of the focus point was examined during a change of the ambient temperature by about $\Delta T \approx -0.5$ K.

3.1 LSF maximum shift

In Figure 5, the LSF curves of 130 repeated focus scans are shown "from above". Each horizontal line represents the

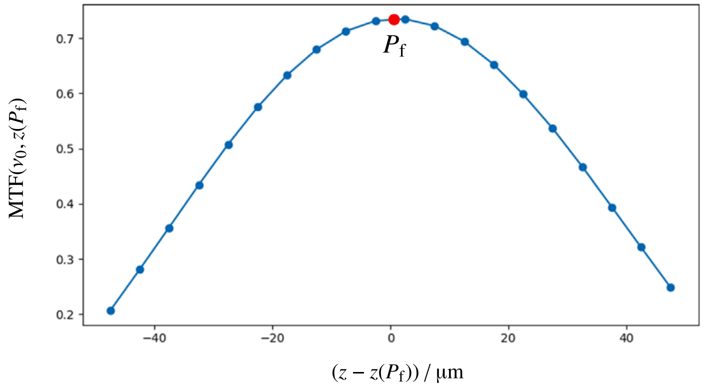


Figure 3. Plot of a typical focus scan depicting the MTF value for a selected spatial frequency ν_0 vs. z-axis position relative to the focus point position $z(P_f)$ determined using a polynomial fit.

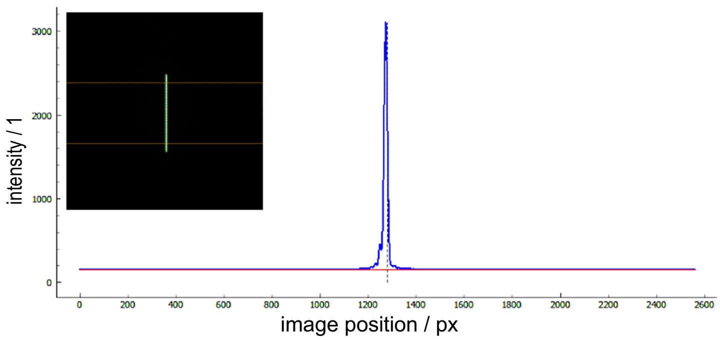


Figure 4. Line spread function (LSF) depicting the intensity distribution in the camera image (inset top left).

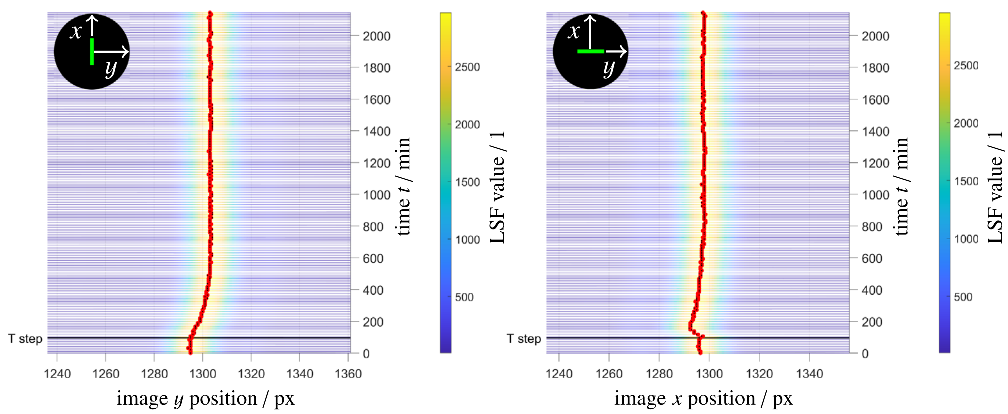


Figure 5. Waterfall plot of the LSF curves of repeated focus scans displaying the shift of the LSF maximum after changing the ambient temperature. Left: tangential slit object orientation, right: sagittal slit object orientation. Coordinates given refer to the measurement setup coordinate system (cf. Fig. 1).

LSF at the focus point position, the line color denotes the intensity value, and the points marked in red indicate the respective maximum of each LSF plot.

After the temperature change the position of the LSF maximum shifts by 10 px (≈1.35 µm) in the horizontal direction perpendicular to the optical axis (y) and 6 px (≈ 0.8 µm) in the vertical direction perpendicular to the optical axis (x). It can be seen that the LSF maximum shift in the vertical direction vanishes after about 10 h whereas the horizontal offset remains. This denotes the different expansion behavior of the components of the experimental setup.

3.2 Focus point shift

Figure 6 shows the results of the 130 repeated focus scans. Like in Figure 5 each line represents a single focus scan and its color the MTF value. The points marked in red indicate the respective MTF maximum of each focus scan plot.

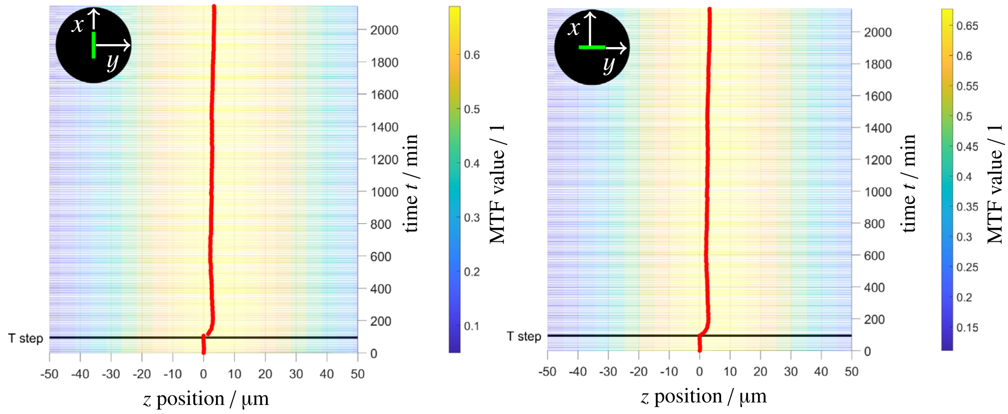


Figure 6. Waterfall plot of the MTF curves of repeated focus scans displaying the shift of the LSF maximum after changing the ambient temperature. Left: tangential slit object orientation, right: sagittal slit object orientation. Coordinates given refer to the measurement setup coordinate system (cf. Fig. 1).

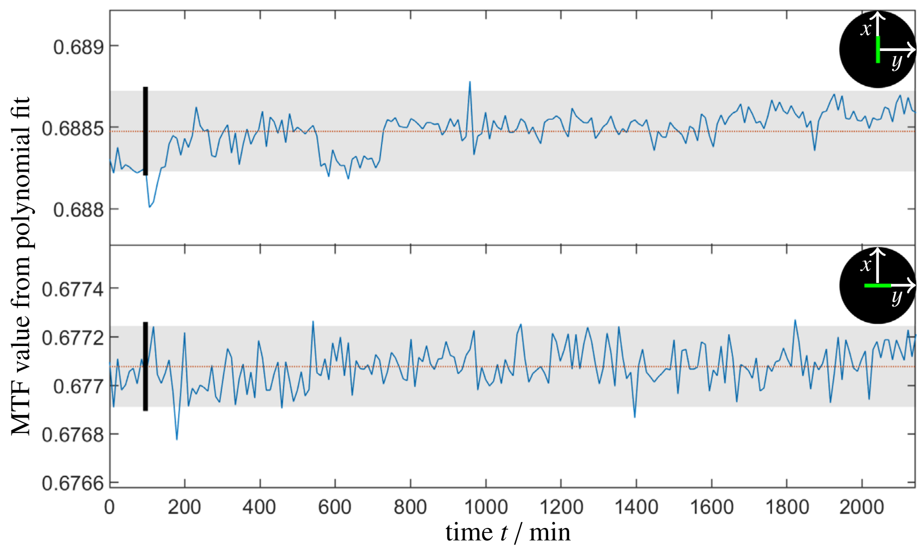


Figure 7. Maximum MTF value of the repeated focus scans obtained from polynomial fit of the measurement data. Top: tangential slit object orientation, bottom: sagittal slit object orientation. Coordinates given refer to the measurement setup coordinate system (cf. Fig. 1).

Also in the z direction (i.e. along the optical axis), a shift of the maximum position can be observed. It reaches a maximum deflection of about 3.5 µm approximately 2 h after changing the ambient temperature. Owing to the vanishing contribution of the x component shift, the MTF maximum deflection decreases slightly and reaches equilibrium after about 10 h.

3.3 Effect on the MTF value at the focus point

To assess the effect of the focus point shift on the MTF value two different cases are taken into account: The absolute MTF maximum value determined from the polynomial fit of the measurement data does not change significantly during the repeated focus scans (Fig. 7).

However, the repeated focus scans are started using the previously determined focus point position as the scan center. Thus, at the center position of the initial focus scan the maximum MTF value is obtained only in the case the focus point position does not change significantly. As the focus point moves owing to the temperature change, so does the MTF versus z curve. Thus, the MTF value detected at the initially set center position regarded as focus point decreases, as shown in Figure 8. In comparison to the absolute MTF value for the evaluation frequency obtained from polynomial fit, the changes due to the focal point shift are an order of magnitude greater than the changes in the absolute value due to the slightly altered beam path. Although relatively small, this still requires the ambient temperature to be kept stable for reliable measurement of the MTF.

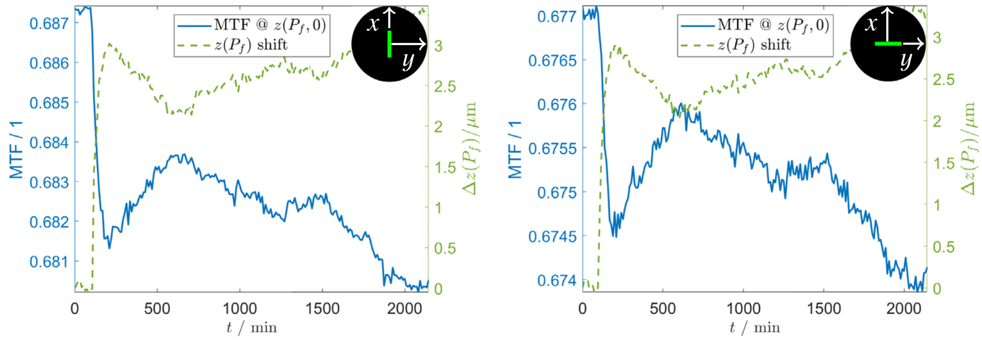


Figure 8. MTF value detected at the position set as focus scan center. Initially this position represented the focus point, i.e. the z position with the highest MTF value. Coordinates given refer to the measurement setup coordinate system (cf. Fig. 1).

4 Conclusion

In this contribution, results of a change in the ambient temperature have been presented. The temperature-dependent shift of the focus point leads to a pronounced decrease of the MTF value obtained at the position that is considered as the focus point. This makes the stability of the ambient temperature a crucial condition for the uncertainty of the MTF measurement. It should be ensured that the ambient temperature has been kept constant during a measurement as well as for several hours before.

Funding

This research received no external funding.

Conflicts of interest

The authors have no conflicts of interest to disclose.

Data availability statement

The data is available on request from the corresponding author.

Author contribution statement

Following the CRediT taxonomy, the contributions of each author are as follows: Hanno Dierke – Conceptualization, investigation, methodology, software, validation, visualization, and writing/review & editing of the original draft. Markus Schake – Methodology, software, supervision, validation, and reviewing.

References

1 Goodman JW, in *Introduction to Fourier optics*, 2nd edn. (McGraw Hill, New York, 1996).
2 Boreman GD, in *Modulation transfer function in optical and electro-optical systems*, 1st edn. (SPIE, USA, 2001). https://doi.org/10.1117/3.419857.
3 International Organization for Standardization, *ISO 9335:2012: Optics and photonics – optical transfer function – principles and procedures of measurement* (2012). https://www.iso.org/standard/57565.html.
4 Schenker M, Stavridis M, Schulz M, Tutsch R, Effects of misalignments on the modulation transfer function measurement of camera lenses analyzed in optomechanical simulations, *Opt. Eng.* **59**, 1 (2020). https://doi.org/10.1117/1.OE.59.3.034101.
5 Schake M, Schulz M, Influence of camera temperature on MTF measurements with finite image distance, *EPJ Web Conf.* **266**, 10018 (2022). https://doi.org10.1051/epjconf/202226610018.
6 Dierke H, Schake M, Improved alignment of the setup for traceable measurements of the modulation transfer function (MTF), *SPIE Optical Metrology 2023 Proc. Optical Measurement Systems for Industrial Inspection XIII* 1261815 (2023). https://doi.org/10.1117/12.2673632.
7 Dierke H, Schake M, Bestimmung des Fokuspunkts bei Messung der Modulationstransferfunktion MTF, in *DGaO – Proceedings 2023* (DGaO, Berlin, 2023), p. 124 B43. https://d-nb.info/1299758568/34.
8 Schake M, Schulz M, Influence of camera exposure time on MTF measurements in not ideally linear systems, in *DGaO – Proceedings 2022* (DGaO, Berlin, 2022), p. 123 B20. https://d-nb.info/1267641754/34.