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# Ultra-Fast MTF Test for High-Volume Production of CMOS Imaging Cameras

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## ABSTRACT

During the last years compact CMOS imaging cameras have grown into high volume applications such as mobile phones, PDAs, etc. In order to insure a constant quality of the lenses of the cameras, MTF is used as a figure of merit. MTF is a polychromatic, objective test for imaging lens quality including diffraction effects, system aberrations and surface defects as well. The draw back of MTF testing is that the proper measurement of the lens MTF is quite cumbersome and time consuming. In the current investigation we designed, produced and tested a new semi-automated MTF set up that is able to measure the polychromatic lens system MTF at 6 or more field points at best focus in less than 6 seconds. The computed MTF is a real diffraction MTF derived from a line spread function (not merely a contrast measurement). This enables lens manufactures to perform 100% MTF testing even in high volume applications. Using statistic tools to analyze the data also gives possibility to find even small systematic errors in the production like shift or tilt of lenses and lens elements. Using this as feedback the quality of the product can be increased. The system is very compact and can be put easily in an assembly line. Besides design and test of the MTF set up correlation experiments between several testers have been carried out. A correlation of better than 6 % points for all tested systems at all fields has been achieved.

Keywords: MTF testing, production test equipment, imaging optics, high volume manufacturing.

## 1. INTRODUCTION

Over the past decades the concept of Optical Transfer Function (OTF) has been proven to be a very powerful concept for characterizing imaging optics. The advantages of the OTF are that it is an objective measure of image quality. It is polychromatic and combines diffraction-, aberration- and even stray light effects influencing the image quality. However the OTF is usually only measured at one field point and is strongly depending on the focus position. Therefore usually several measurements are needed in order to fully characterize an imaging lens. Also a single OTF measurement usually takes a considerable amount of time.

Moving imaging applications into high volume markets such as mobile phones and PDAs, and still applying OTF as main quality control poses a new challenge. In the present article we present a solution that measures the OTF in an extremely fast way. This way even at very high manufacturing volumes 100% OTF measurement can be applied as quality control.

# 2. CONCEPT OF OPTICAL TRANSFER FUNCTION

## 2.1 GENERAL CONCEPT

The optical transfer Function of a system can be understood as the response function of the optical system to a known input. This known input can be in the form of a perfect point source. However in this article we will take a line source as input. The reason for that is a better signal to noise ratio of the signal. The input line will be illuminated with incoherent light. Furthermore it will be assumed that the optical system is a linear system. Under these circumstances the image of the line, the so called Line Spread Function (LSF) $g(x_1)$ can be understood as a convolution between the object line $f(x)$ and the response function of the system, $h(x,x_1)$

$$g(x_1) = f(x) * h(x, x_1) \tag{1a}$$

or in integral form

$$g(x_1) = \int_{-\infty}^{+\infty} f(x)\, h(x_1 - x)\, dx\,. \tag{1b}$$

Making use of the assumption of linear systems and applying Fourier theory Eq. (1a) can be re-written in Fourier space as the product of the Fourier transforms

$$G(u) = F(u) \cdot H(u)\,. \tag{2}$$

In Fourier space H(u) is called the transfer function and for an optical system H(u) is the optical transfer function OTF. From this it becomes clear that the OTF is a complex function with a real and imaginary part. Writing down the OTF gives Eq. (3).

$$OTF(u) = |H(u)|\, e^{i\Phi(u)} = MTF(u) \cdot PTF(u) \tag{3}$$

The real part of the OTF is called the Modulation Transfer Function, MTF, and the complex part of it is the Phase Transfer Function, PTF. In summary the following graphical representation of gaining the OTF can be made.

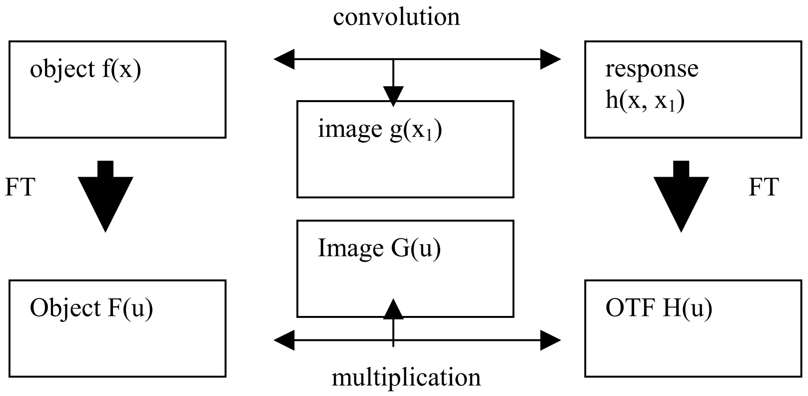


Figure 1: Connection between object, image and OTF.

Looking at Fig. 1 there are several ways to get to the OTF. One way would be to record the image of a well-known object and then perform a deconvolution in order to get to the system response function. Afterwards the OTF can be calculated via Fourier transform of the response function. This path is rather difficult since it involves the deconvolution and also Fourier transform.

The alternative path is to first Fourier transform the object, then Fourier transform the image and calculate the OTF directly by dividing image Fourier transform by object Fourier transform.

$$OTF(u)=\frac{G(u)}{F(u)}. \tag{4}$$

### 2.2 VIDEO MTF

In the case presented here some additional conditions have to be fulfilled and some more system parameters have to be taken into account. First of all the object slit does have a finite slit width. Besides the finite slit width the LSF is magnified by a video microscope and then analyzed. The magnification and optical response of the video microscope has to be included and finally the characteristic of the detector. Since a CCD camera is used as a detector the response function of the CCD needs to be included as well.

Looking at all of these factors the following formula can be derived

$$G(u) = F'(u) \cdot OTF(u) \cdot M(u) \cdot D(u), \tag{5}$$

with F'(u) the object line of finite width, M(u) the OTF of the video microscope optics and D(u) the transfer function of the CCD detector. The final OTF of the system under test is then computed as

$$OTF(u)=\frac{G(u)}{F'(u)\cdot M(u)\cdot D(u)}. \tag{6}$$

The Fourier transform of a slit object can be analytically calculated

$$F'(u)=\frac{\sin(ka)}{ka}=\mathrm{sinc}(ka), \tag{7}$$

with $a$ being half the width of the object slit. It has to be given that the slit is chosen sufficiently small that the sinc – function stays sufficiently away from zero. For the optics of the video microscope a very well corrected microscope objective is taken. This way the influence of the magnifying optics can be neglected. The transfer function of the CCD camera needs to be measured and taken into account. A possible way of doing so is described in the literature[1].

## 3. PRODUCTION MEASUREMENT SET-UP

### 3.1 OPTO – MECHANICS

Basic requirements for the MTF production set up were:

- full MTF calculation (not only contrast measurement)
- multiple fields
- polychromatic
- autofocus
- fast (total measurement time less than 6 seconds)
- fast loading and unloading
- operator user interface

Taking all these requirements into account, it was chosen to design and manufacture a MTF system that is based upon projection**.** Fig. 2 shows a drawing of such a system. Through a fiber system followed by illumination optics a test target is uniformly illuminated. The test target is shown in Fig. 3. It is manufactured using photolithography. It is also specifically designed for each different lens that has to be tested. On the test target 6 different locations are defined. At each of these areas of test, 2 orthogonal lines are implemented, such that MTF in tangential and sagittal direction can be measured. In the center an additional line is added for measuring the effective focal length of the lens under test (LUT).

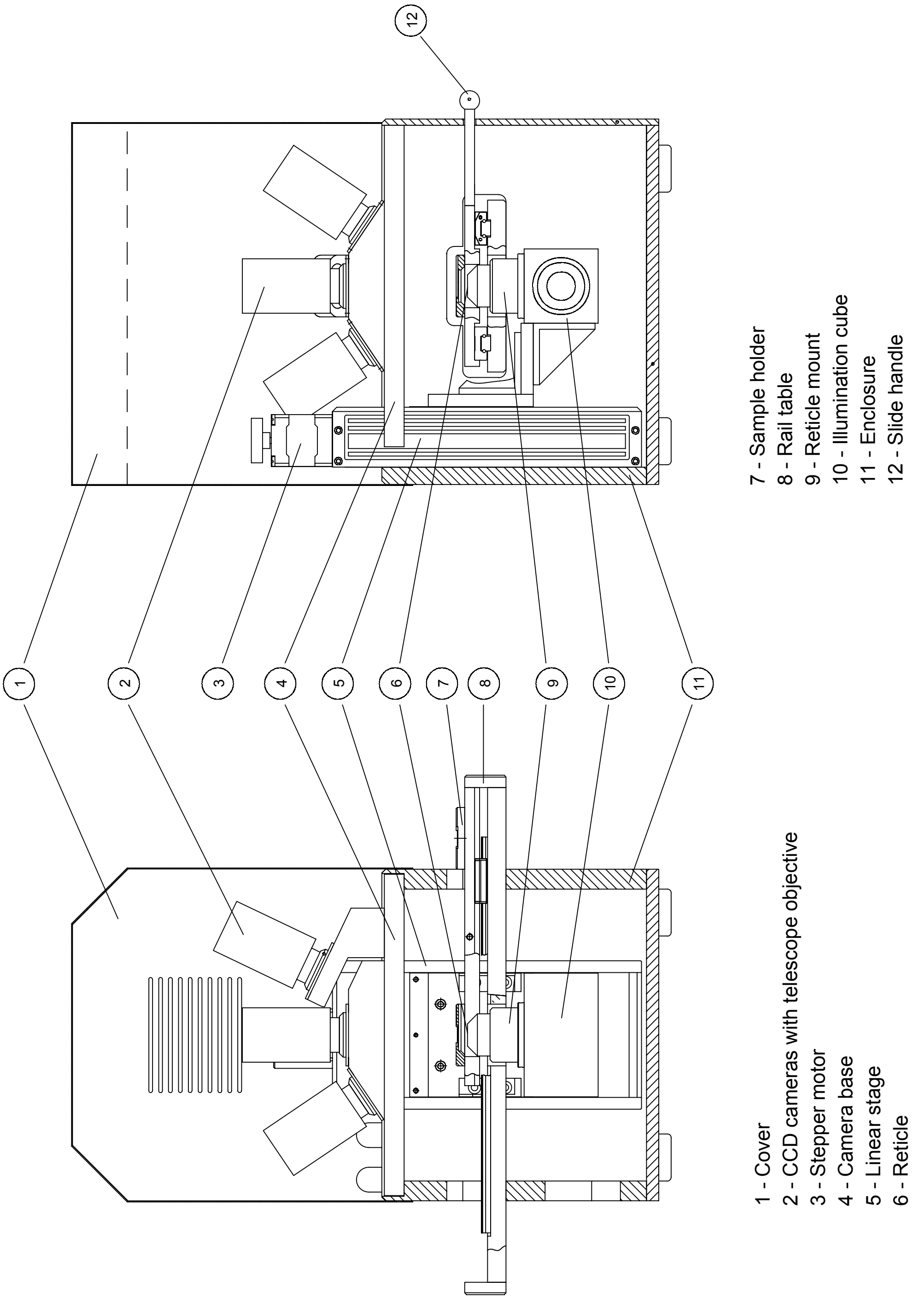


Figure 2: A typical MTF tester design. The whole illumination and test target fixture is mounted on a stage that can move in z-direction (light direction). This is used to adjust for optimum focus position.

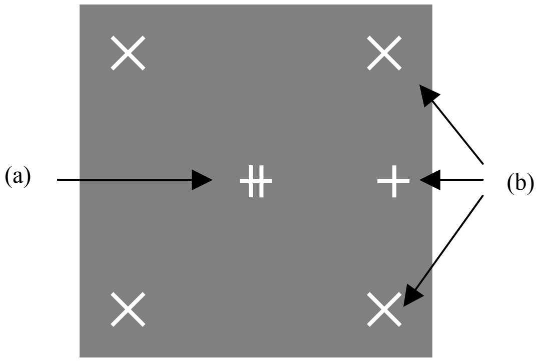


Figure 3: Test target with (a) on-axis pattern elements, (b) off-axis pattern elements.

Above the test target the LUT is mounted on a fixture that can be moved in and out of the tester. If the test target is placed in the focal plane of the lens, light originating at the different field positions is leaving the lens under defined angles. The angles are determined by the properties of the lens together with the test target field positions. CCD cameras are placed at these angles. The auxiliary optics in front of the CCD cameras images the line spread functions (LSF) of the system under test onto the CCD cameras. These LSFs are then evaluated using advanced software algorithms.

Since many parameters influence the measured MTF, special attention has to be paid to the following design parameters.

(a) Fixture
The fixture with the lens under test has to be parallel to the test target. Furthermore it is desirable that there are mechanical references at the mount of the LUT. If LUT and test target are not aligned parallel to each other, tilt is introduced and wrong MTF readings are the result. Having the mechanical reference points supports getting the LUTs always to the same measurement position. The CCD cameras with the auxiliary optics should be aligned such that the light coming form the LUT enters this sub-system on-axis. If this is not the case, the auxiliary optics is used off – axis and might introduce aberrations contributing to the MTF, and not originating from the LUT.

(b) Auxiliary Optics
Since the MTF of the LUT needs to be measured, the auxiliary optics has to be characterized very well. Especially the focal length of the lens needs to be known very precisely and also the CCD camera has to be placed exactly in the focal plane of the auxiliary optics. If this is not realized, a wrong magnification factor will enter the MTF evaluation, giving a wrong spatial frequency calibration.

(c) CCD Camera
At least, since a CCD camera is used as detector, the MTF of the CCD camera needs to be known as well and incorporated in the MTF evaluation[1]. If this is not done in a careful way, again errors in the MTF evaluation will occur, especially at higher spatial frequencies.

In order to implement all these items a special installation- and calibration routine has been developed.

### 3.2 SOFTWARE

The software for the MTF tester is specially designed for the use in a production line environment. The main characteristics are

(a) Fast measuring time: The EFL measurement and MTF evaluations on-axis and at 5 off-axis positions sagittal and tangential are done within 6 seconds.

(b) Reliability: The error proof design allows maintenance free operation 24 hours a day.

(c) Ease of use: The software can be used by technically non-skilled operators who have been trained at the instrument for about half an hour. Simple pass/fail signals are generated according to acceptance levels defined in the settings.

(d) Accuracy: The measurement accuracy was proven to be well within the tolerance of 5% given as measurement uncertainty by the PTB (Physikalisch-Technische Bundesanstalt) on a master sample set.

The software reads and displays the video images from 6 CCD cameras connected to one frame grabber. The reticle is moved by a motorized linear stage controlled via serial port interface. An advanced autofocus algorithm evaluates the center camera image and performs a through-focus scan between user-defined limits. To compensate production or positioning tolerances, these limits are automatically adjusted if necessary. The position with maximum MTF at a predefined spatial frequency is determined and the reticle is moved to this position. A graphical display shows the through-focus scan curve and the best focus position for verification by the operator. The software automatically locates the images of the test structures within the video frames and determines the measurement areas of interest. After the autofocus procedure, the sample EFL is determined by measuring the magnification of the central test structure. It is also possible to measure the MTF at a other focal positions than at highest MTF on-axis. If a so-called defocus value is given in the instrument settings, the stage moves to this defocus position before doing the MTF evaluation. The MTF evaluation is done by means of a Fast Fourier Transformation (FFT) of the LSF. Two LSF, for sagittal and tangential direction, are evaluated from the crosshair target. The measurement results are saved to disk and can be loaded into spreadsheets for statistical evaluation.

A unique feature of the software is a polar plot of MTF vs. azimuth angle. With this plot, an asymmetry within the sample (e.g. centering error) or a misalignment is easily recognized.

Due to the application in a production environment, user interventions are kept to a minimum. After having inserted the sample, the complete measurement cycle is invoked by a single key press. While setting up the instrument the user may also move the stage manually or perform a coarse autofocus scan to search for the sample's focal plane.

The software employs three different password protected security levels to prevent the unintentional change of important instrument settings. The standard operator may only read and execute predefined setting files. The supervisor may change measurement parameters, pass/fail criteria and non-critical instrument settings, and create in this way settings files for the standard operator. The third level is restricted to the manufacturer who has access to fixed and critical instrument settings, such as calibration values.

## 4. MEASUREMENT RESULTS

Table 1 shows representative repeatability measurements of one sample measured on one MTF production tester. The sample has been measured 5 times with this system. After each single measurement the sample was removed and placed again into the MTF tester for the following measurement.

The MTF tester measures the complete MTF curves on-axis and at 5 off-axis positions. All MTF values refer to a spatial frequency of 50 lp/mm.

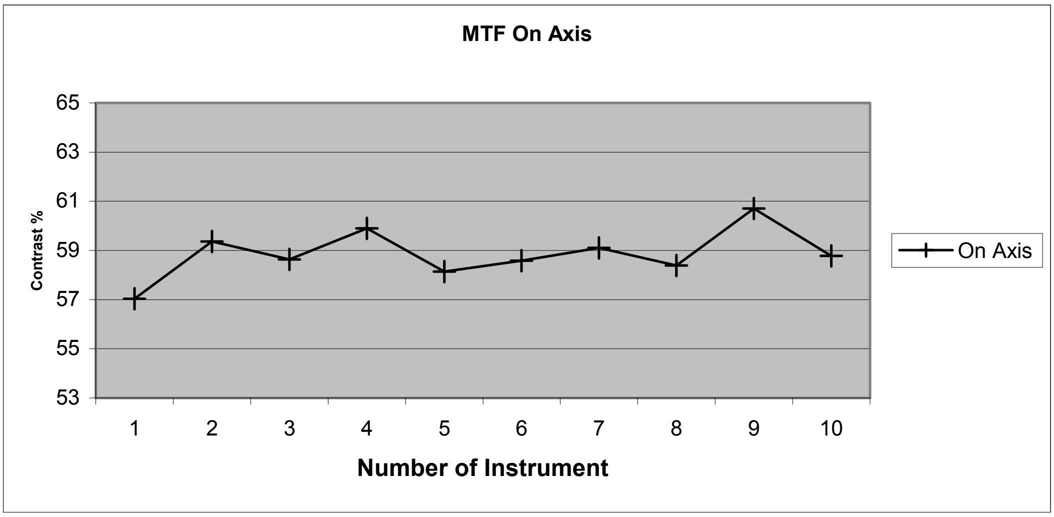
| # | EFL | On- Axis | 2 T | 2 S | 3 T | 3 S | 4 T | 4 S | 5 T | 5 S | 6 T | 6 S |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 3,495 | 58,7 | 25,5 | 29,3 | 16,8 | 20,6 | 16,9 | 12,6 | 28 | 18,6 | 36,7 | 26,2 |
| 2 | 3,495 | 59,8 | 25,6 | 29,9 | 16,9 | 20,7 | 17,2 | 13,1 | 28 | 18,1 | 37,3 | 26,7 |
| 3 | 3,495 | 59,2 | 25,4 | 29,5 | 16,7 | 20,7 | 17,1 | 12,6 | 28,3 | 17,6 | 37,1 | 26,4 |
| 4 | 3,496 | 58,8 | 25,5 | 30 | 16,5 | 20,1 | 16,9 | 12,8 | 28 | 18,6 | 37,5 | 25,9 |
| 5 | 3,496 | 60,3 | 25,9 | 28,4 | 16,7 | 20,8 | 17,2 | 13 | 28,2 | 18,5 | 37,6 | 27,2 |
| Average | 3,4954 | 59,4 | 25,6 | 29,4 | 16,7 | 20,6 | 17,1 | 12,8 | 28,1 | 18,3 | 37,2 | 26,5 |
| Delta | 0,001 | 1,6 | 0,5 | 1,6 | 0,4 | 0,7 | 0,3 | 0,5 | 0,3 | 1 | 0,9 | 1,3 |

Table 1: MTF measured with one MTF tester.

Each line shows the results of one measurement. Columns display the measurement positions and directions (T: tangential, S: sagittal). Delta gives the difference between the maximum and minimum value of one field position.

## 4.1 CORRELATION BETWEEN SEVERAL MTF – TESTERS

As an example the results of the correlation tests for a particular sample are displayed in Fig. 4. The plots show the MTF values for this sample measured on 10 different MTF testers. Each line refers to one position in the field. It can be seen that the results for all 10 instruments agree within a range of ±3%.



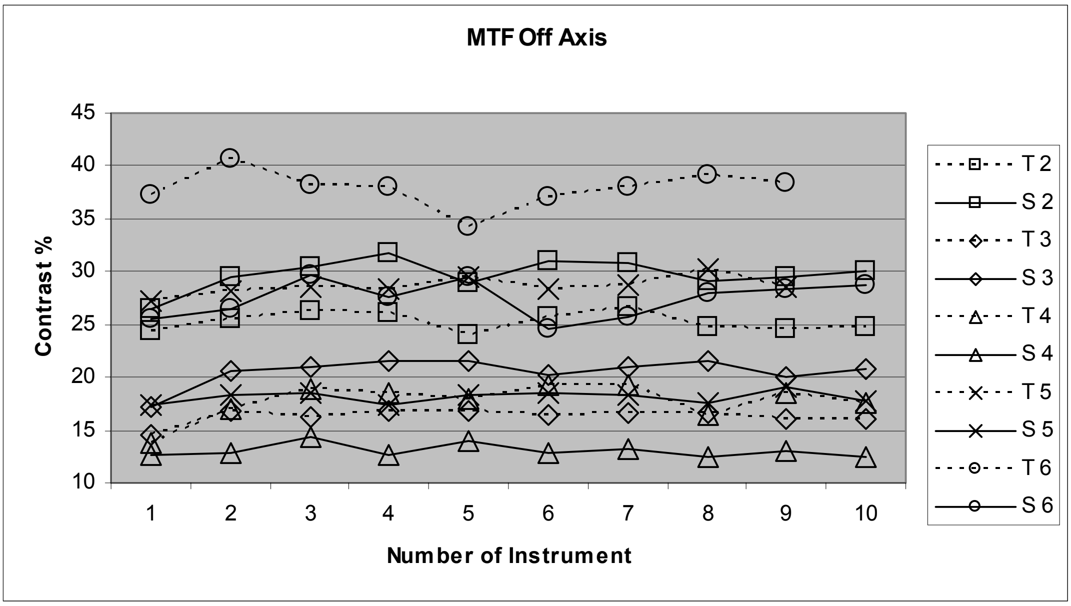


Figure 4: MTF values for a single sample measured on different test instruments.

## 5. CONCLUSION

With the production MTF tester a very powerful tool was created to measure MTF of compact imaging lenses. A diffraction based MTF is computed and not merely some contrast measured. Measurement of 6 different field positions and finding a specified focus setting is done in less than 6 seconds. With this measurement time a 100% quality control based on MTF is feasible.

It has also been shown that different MTF testers correlate within 6 percent points. This is a very good correlation, keeping in mind that the results are from different machines, operated by different operators and using lenses that are not particularly designed with a fixed mechanical reference. As to our knowledge, this kind of correlation has not been published before.

## 6. REFERENCES

1. Brueggemann, C., Kross, J., “Charakterisierung von CCD-Kameras”, F&M **104**, 610-614, 1996 (in German).