Improved Modulation Transfer Function evaluation method of a camera at any field point with a scanning tilted knife edge

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ABSTRACT

Modulating Transfer Function (MTF) has always been very important and useful for objectives quality definition and focal plane settings. This measurand provides the most relevant information on the optimized design and manufacturing of an optical system or the correct focus of a camera. MTF also gives out essential information on which defaults or aberrations appear on an optical objective, and so enables to diagnose potential design or manufacturing issues on a production line or R&D prototype.

Test benches and algorithms have been defined and developed in order to satisfy the growing needs in optical objectives qualification as the latter become more and more critical in their accuracy and quality specification.

Many methods are used to evaluate the Modulating Transfer Function. Slit imaging and scanning on a camera, MTF evaluation thanks to wavefront measurement or imaging fixed slanted knife edge on the detector of the camera. All these methods have pros and cons, some lack in resolution, accuracy or don't enable to compare simulated MTF curves with real measured data. These methods are firstly reminded in this paper.

HGH has recently developed an improved and mixed version of a scanning technique used on a slanted knife edge giving a more accurate, ergonomic, high resolution and precise Line Spread Function (LSF) and one axis MTF measurement of a camera. A selected single pixel corresponding to a precise field point of the camera is scanned with sub pixelic resolution by the tilted knife edge thus enabling an optimized accuracy for LSF and MTF curves. The experimental protocol which requires a high-performance collimator, a scanning wheel device and a camera set up is detailed in this paper. Explained simulations are done to prove the under 1% accuracy of this method with regards to the different characteristics of the camera. All the parameters of this improved measurement technique are described and their effect criticized to give out all the result influence of these variables. These simulations and the algorithms used are then confronted to real measurements on a camera thanks to a mirror-based collimator and a scanning wheel device equipped with a slanted knife edge target.

Keywords: Modulation Transfer Function, Line Spread Function, Edge Spread function, Optical quality, Optics control and qualification, scanning MTF, MTF measurement Accuracy.

1. DEFINITION OF THE MODULATION TRANSFER FUNCTION (MTF)

1.1 General definition reminder [1]

The modulation transfer function is the magnitude response of the optical system to sinusoids of different spatial frequencies. When we analyze an optical system in the frequency domain, we consider the imaging of sinewave inputs (Figure 1) rather than point objects.

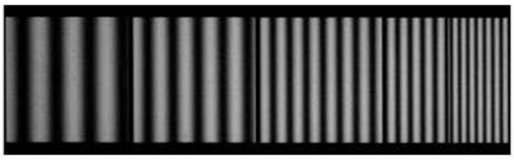


Figure 1 : *Sinewave target of various spatial frequencies.*

A linear shift-invariant optical system images a sinusoid as another sinusoid. The limited spatial resolution of the optical system results in a decrease in the modulation depth *M* of the image relative to what is was in the object distribution (Fig. 1.9). Modulation depth is defined as the amplitude of the irradiance variation divided by the bias level:

$$M = \frac{A_{max} - A_{min}}{A_{max} + A_{min}} = \frac{2 \times ac\ component}{2 \times dc\ component} = \frac{ac}{dc}$$

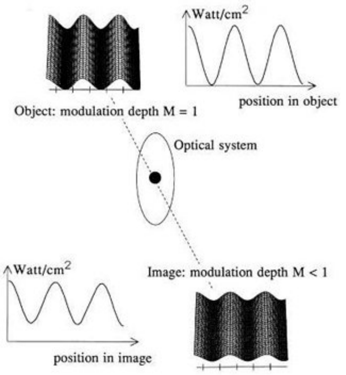


Figure 2 : *Modulation depth decreases going from object to image.*

Figure 3 shows that modulation depth is a measure of contrast, with

$$M \to 0 \ as \ A_{max} - A_{min} \to 0 \ and \ M \to 1 \ as \ A_{min} \to 0 \tag{1}$$

Low levels of modulation depth are harder to discern against the unavoidable levels of noise inherent in any practical system.

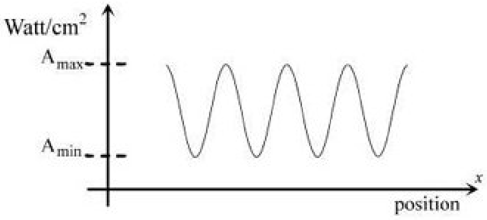


Figure 3 : *Definition of modulation depth.*

The finite size of the impulse response of the optical system causes a filling in of the valleys of the sinusoid and a lowering of the peak levels. The effect of this is to decrease the modulation depth in the image compared to the object. Defining the modulation transfer (MT) as the ratio of modulation in the image to that in the object,

$$MT \equiv \frac{M_{image}}{M_{object}} \tag{2}$$

we find that the reduction of modulation transfer is spatial-frequency dependent. The limited resolution of the optics is more important at high spatial frequencies, where the scale of the detail is smaller. As seen in Figure 4, when we plot modulation transfer against spatial frequency, we obtain the MTF, generally a decreasing function of spatial frequency. The MTF is the image modulation as a function of spatial frequency (assuming a constant object modulation),

$$MTF(\xi) \equiv \frac{M_{image}(\xi)}{M_{object}} \tag{3}$$

The *M* of the object waveform does not need to be unity—if a lower input modulation is used, then the image modulation will be proportionally lower.

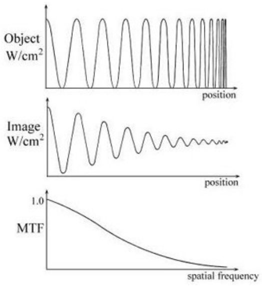


Figure 4 *Modulation transfer function is the decrease of modulation depth with increasing frequency.*

1.2 Applications of MTF measurement

Numerous applications and stakes are linked to MTF evaluation. Hereafter are some of these:

- Optical design performance

When designing an optical system, it is necessary to be able to evaluate the performances of the design like field of view, image resolution, distortion, detection ranges… Many optical design softwares like Zemax (Zemax LLC) or CODE V (Synopsys) enable to simulate the optics MTF curves:

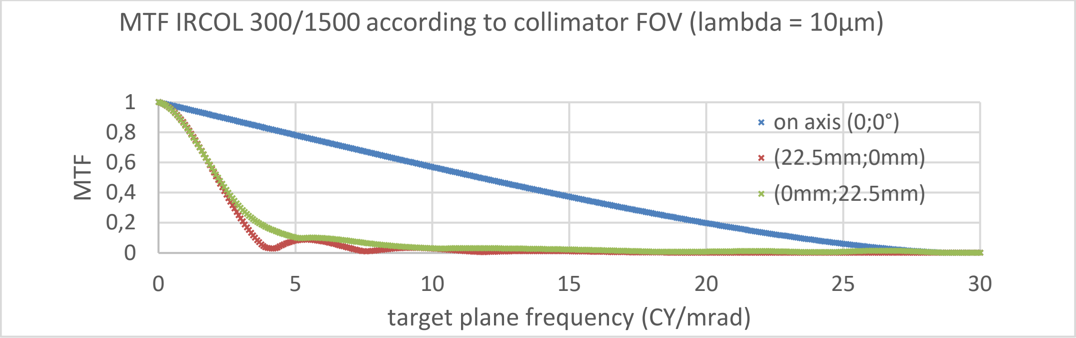


Figure 5 *Example of MTF curves simulation of an HGH collimator IRCOL 300-1500 at different fields of view*

MTF contributes to directly measuring and evaluating the resolution detection range of the optical system looking at a far object. Indeed, it gives out the information of the contrast seen by the system of a physical object with a characteristic size A positioned at a distance D. The equivalent frequency f of this object can be defined as:

$$f = Atan\left(\frac{D}{A}\right) \approx \frac{D}{A} \ (cy/rad) \tag{4}$$

In thermal imaging, it is possible to directly link MRTD (Minimum Resolvable Temperature Difference) curves to MTF. Thanks to the Johnson criteria and MRTD one can evaluate Detection, Recognition and Identification ranges (DRI ranges) of any given object seen by this optical system.

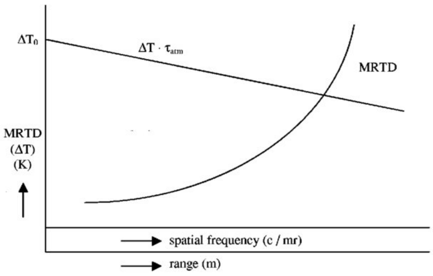


Figure 6 : *DRI range evaluation with MRTD curves directly dependent to MTF [2]*

- Camera setting and checking

Optimizing MTF curves enables a user to set a camera like its focus for example. By visualizing the MTF curve while setting the lens of a camera, the user just has to look at which position of the lens the MTF curve is maximized.

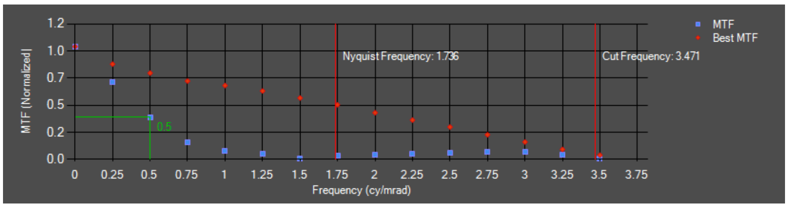


Figure 7 : *current MTF (blue) and best MTF (red) curves acquired while setting the focus lens*

2. MTF MEASUREMENT EXISTING METHODS

In order to acquire MTF of a lens or camera, different methods and techniques are possible. Here are 2 examples of these methods.

2.1 Imaging slit technique

This method is essentially used to test lens quality.

The technique is to image a thin slit on a camera detector with the lens to be qualified or under test (LUT). Hereafter is a scheme of the experimental protocol:

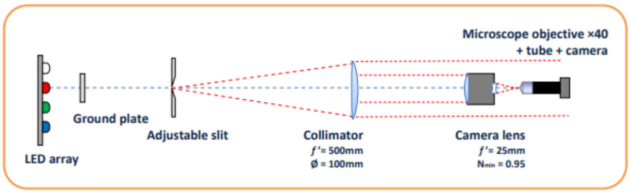


Figure 8 : experimental protocol of the imaging slit technique and photo [3]

A slit is imaged thanks to a collimator and the lens under test (LUT) on a microscope objective and camera detector. The general idea is to generate the Line Spread Function (LSF) generated by the lens under test.

The LSF represents the Point Spread Function (PSF) of the lens under test over a single direction. If the slit is vertical the LSF corresponds to the PSF in the horizontal direction (X) and if the slit is horizontal, the LSF corresponds to the PSF in the vertical direction (Y).

Calculating the Fourier transform of the LSF gives the MTF in the selected direction:

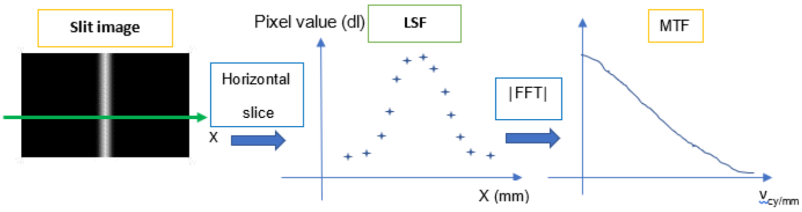


Figure 9 : scheme of the algorithm of the slit imaging technique

The method has the advantage of being quick and the algorithm simple (no image modification or reconstruction is done to evaluate the LSF). The drawbacks of this method are that not all optical systems are testable on this bench. Indeed, the following parameters are to be taken into account:

- Size of the slit: The slit needs to be sufficiently wide so that minimum flux goes through the system and camera is sensitive enough to acquire the LSF.
- Pixel size of the camera and focal lengths of collimator, lens under test and microscope objective: these parameters influence the resolution and horizontal dynamic range of the LSF and thus resolution and horizontal dynamic range of the MTF curve. Indeed, if the slit is small enough so that its image in the image focal plane is diffraction limited, the microscope objective must have a sufficient magnification so that the LSF takes at least 8 pixels. That way enough measurement points are used to be able to perform a satisfactory MTF curve and is compatible to a FFT function ($2^3 = 8$ point numbers)
- Aberrations of other optical elements of the bench (collimator and microscope objective). The bench actually measures the MTF of the whole optical chain and the final curve is the combination of MTF curves of all contributors:

$$MTF(\nu) = MTF_{col}(\nu).MTF_{LUT}(\nu).MTF_{objective}(\nu).MTF_{camera}(\nu)$$

$$MTF_{LUT}(\nu) = \frac{MTF(\nu)}{MTF_{objective}(\nu).MTF_{camera}(\nu).MTF_{col}(\nu)} \tag{5}$$

According to (5) it is necessary to know the MTF of each optical element of the test bench in order to accurately evaluate MTF_{LUT}. Also, if the cut off frequency of one of these elements is lower than the LUT cut off frequency, the test bench ends up measuring the MTF of the limiting element and not of the LUT.

This implies that the cut off frequency and optical quality of the collimator, camera detector and microscope objective must be much higher than the LUT cut off frequency and optical quality (F#, aberration limitation and small pixel size constraints).

2.2 Tilted knife edge technique

This technique consists in imaging a knife edge target onto a camera and using ISO12333 slate-edge methology. The following experimental protocol type is used:

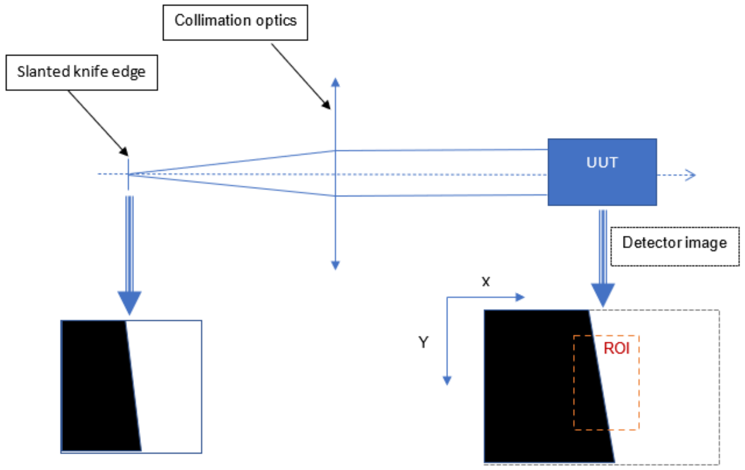


Figure 10 : experimental protocol of the slanted knife edge MTF measurement technique

A slanted knife edge target is collimated so that its image is focused on the detector of the Unit Under Test (UUT) or camera under test. The detector thus sees this slanted knife edge and a Region of Interest (ROI) is defined by the user around the imaged edge.

In this ROI is recovered the Edge Spread Function of the system. From this function we can evaluate the LSF and MTF:

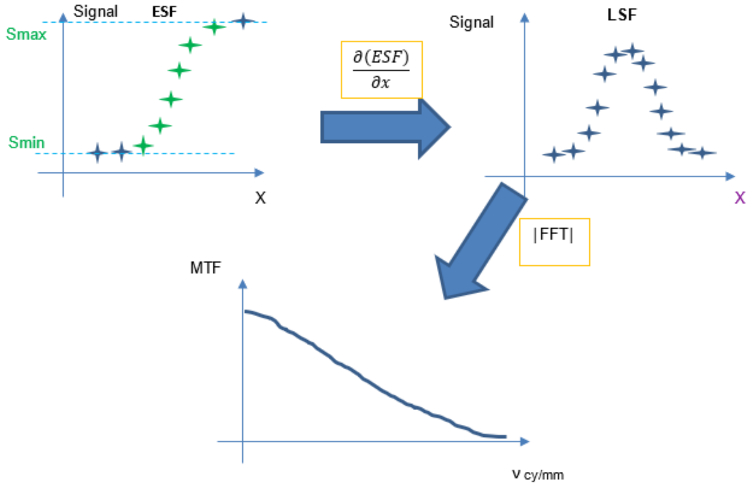


Figure 11 : scheme of the algorithm of the slanted knife edge imaging technique

Having acquired the ESF function over one direction, the derivative of the latter gives the LSF function which thus enables the evaluation of the MTF. The slant of the knife edge acts like a “scan” of the edge over one pixel enabling the evaluation of the signal over one pixel for different positions of the edge on it. Each line of the ROI acts like a “scan” by giving a pixel value of the useful part of the knife edge (the image of the edge is subpixelly shifted thanks to the slant angle).

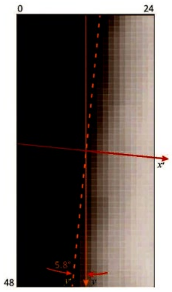
This method permits the acquisition of the useful part of the ESF which are the pixels which values are within the dynamic range of the knife edge image flux (pixels which signal is between Smin and Smax in green in Figure 11).

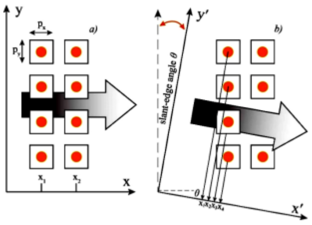
The major advantage of this technique is that it offers a quick and efficient measurement of the MTF without having to select and define a specific target like a slit. On the contrary to a slit, no too low or too high signal level appear with a knife edge. With only one slanted knife edge target, any MTF curve can be acquired for any UUT as long as the collimator aperture is bigger than the UUT’s.

The major drawback of this method is the algorithm that enables to recover the ESF from the selected ROI. Indeed, this method often requires to modify the image spatial characteristics (pixel position according to its signal value) to be able to build this curve. This by definition increases the risk of inaccuracy of MTF.

2.3 Fixed slant knife edge method drawbacks

An example of the ESF construction algorithm consists in a “sort” function of the pixel values in the ROI from smallest value to biggest. The step of the ESF curve would then be equal to δx defined by the following value:





$$\partial x = x2 - x1 = TAN(\theta).pix\_pitch$$

Figure 12 : sampling of the useful part of the ESF inside of the ROI [4]

A typical value of the slant angle θ is 7.125° which gives a sub-pixelic resolution δx of the ESF curve of:

$$\partial x = 1.125.pix\_pitch = \frac{pix\_pitch}{8} \tag{6}$$

8 useful pixel values are used for the ESF construction. If the detector has non uniformities issues (fixed pattern greater than the temporal noise of the system) then some useful pixels may be switched spatially deforming the spatial pattern and order of the ESF function.

Worst case is if bad pixels or dead pixels are present in the ROI. This would result in an ESF with several rising edges which would lead to major errors and inaccuracies in LSF and thus MTF curves. An example is given in the following figure:

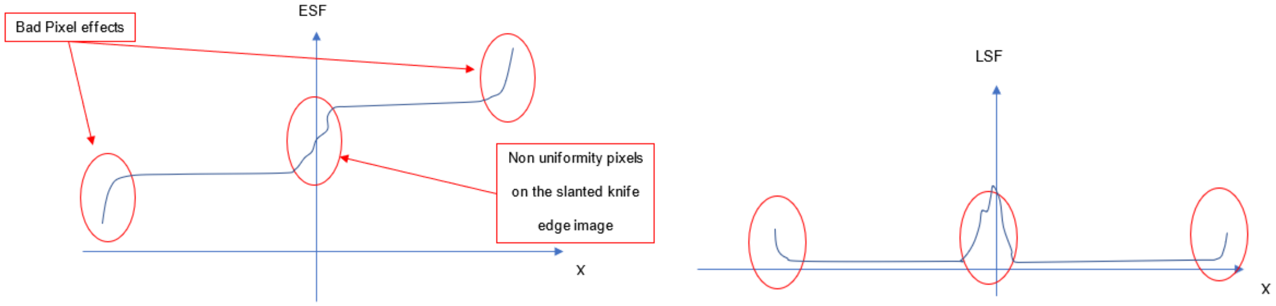


Figure 13 : Errors in LSF linked to spatial error reconstruction of ESF

Hereafter is an example of a real measurement which illustrates this issue:

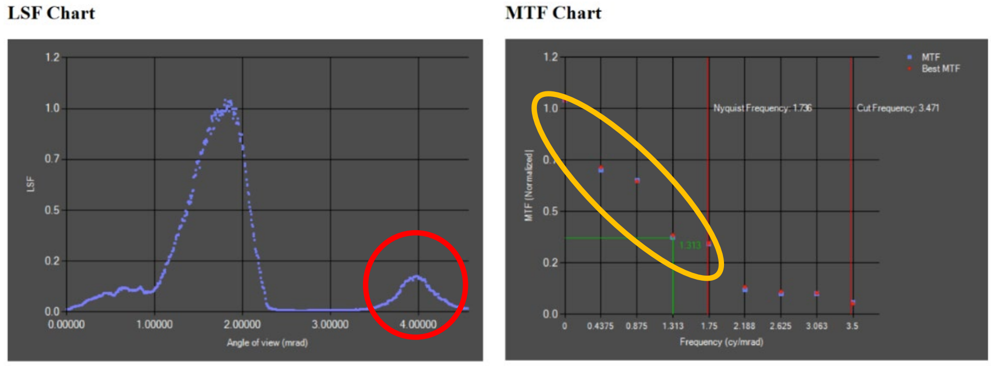


Figure 14 : High frequency bumps in the MTF curve (orange circled) due to unphysical second bumps in the LSF curve (red circled)

Inaccuracies due to these phenomena can be evaluated to over 10% MTF at Nyquist frequency. This value can be a major drawback for high quality lens camera applications.

The main objective of the new method is to have as high accuracy in the measurement as possible with as less as possible high accurate items such as high-performance translation or rotation stages.

3. NEW SCANNING TECHNIQUE MTF MEASUREMENT

3.1 Method explanation and experimental protocol

As explained in paragraph 2, most methods are either with high hardware constraints and so done with high performance thus high cost equipment or lack in accuracy. The objective of this new method is to benefit both lack of constraints with a high accuracy level of MTF. This method is based on the scanning of an imaged tilted knife edge over one pixel:

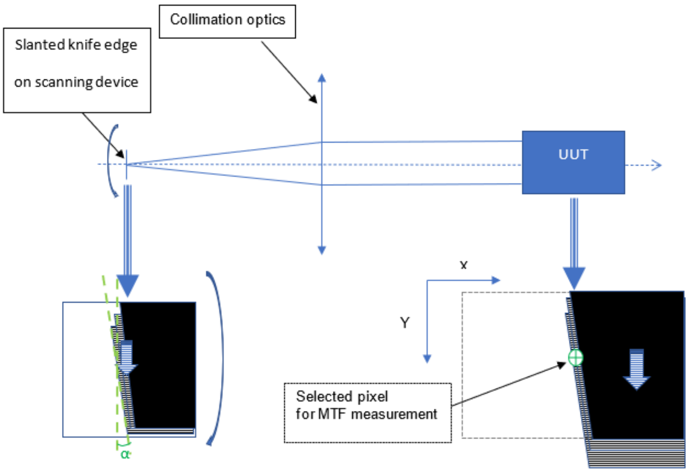


Figure 15 : Slanted knife scanning technique principle.

The general idea is to scan vertically the slanted knife edge so that it simulates a horizontal scan at the selected pixel level.

Figure 16 is a zoomed view of how the pixel sees the knife edge according to the scan position:

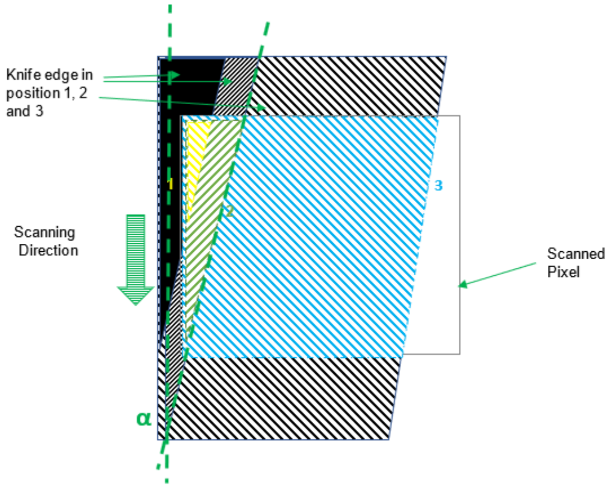


Figure 16 : Area covered by the image of the knife edge on the pixel according to the knife position

Thanks to the slant angle α one can see that a vertical step scan of the knife edge is equivalent to a horizontal scan of the edge onto a pixel.

The knife edge target is assembled on a high-resolution position target wheel located in the focal plane of the collimator.

The usual application of such a target wheel is of course the automated selection of the target at the focus of the collimator, depending on the test. Here, we take the advantage of this already existing target as it is used for a new application: a scanning device enabling accurate LSF and MTF measurements. Consequently, no additional and potentially expensive scanning device is required to do this measurement.

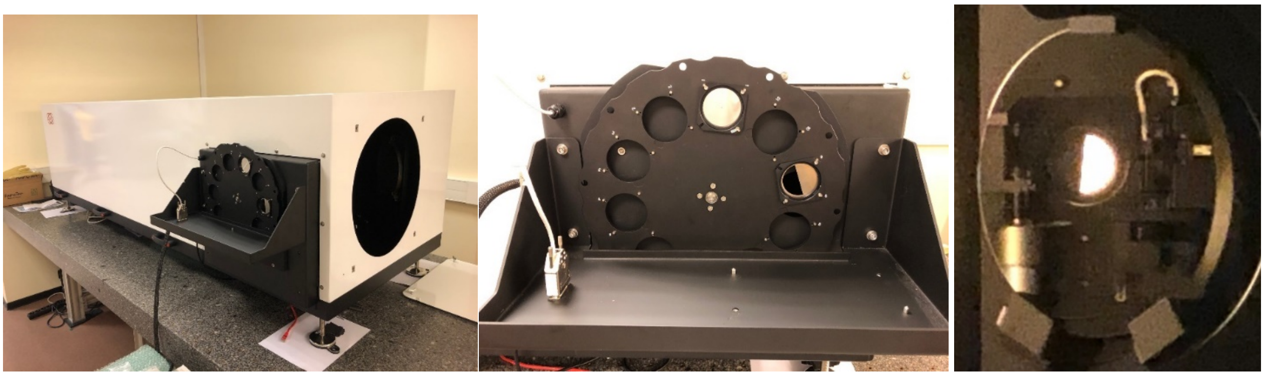


Figure 17 : HGH IRCOL 400-2500 photo (left) with selectable target & scanning system (target wheel) (middle) & UUT view of the slanted knife edge through the collimator (right)

Thanks to this method, the 2 main issues of the methods described in paragraph 2 are solved:

- No spatial reconstruction of the pixels in a ROI and so no errors linked to non-uniformity of the UUT signal,
- Simple experimental protocol with few optical systems for precise MTF measurement.

Furthermore, one can note that this method enables the measurement of the MTF at one-pixel position and not over a series of pixels inside a ROI. This has the advantage of knowing exactly at which field of view position the MTF is measured. Consequently, the comparison of the actually measured MTF curve with a theoretical one obtained from an optics design software is possible.

3.2 Simulation presentation

Having explained the method, it is necessary to confirm its results and performance by identifying bench and all elements of the system that impacts the measurement.

These elements are identified by the following actions linked to the scan method:

- Image position of the image of the knife edge on the selected pixel vs. the knife edge position in the focal plane of the collimator.
- Scan equivalent along X step δx on the pixel: optimization of δx according to the UUT cut off frequency (the δx step and number of points of the overall scan N_scan defines the step and overall frequency ranges of the MTF curve).

Consequently, the involved parameters of the system are:

- Focal length of the UUT (Unit Under Test): F UUT,
- Focal length of the collimator: F col,
- Distance between the center of the target and the rotation axis of the wheel: R_wheel,
- Minimum step of the target wheel encoder,
- Slant angle of the knife edge: α,
- Pixel pitch of the UUT: pix H UUT and pix V UUT and consequently calculated cut off frequency,
- Characteristic wavelength of the UUT,
- F# of the UUT objective and consequently calculated cut off frequency.

We can input all these parameters in order to simulate the ESF of a diffraction limited system:

Parameter name	**Value & unit**	
α	7.125	°
F col	1500	mm
F UUT	100	mm
pix H UUT	8.6	µm
pix V UUT	8.6	µm
Pixel cut off frequency	116.279	cy/mm
Characteristic wavelength of UUT	0.6	µm
F# objective	8	
Cut off frequency objective	208.333333	cy/mm
Number of encoder position for 1 wheel turn	47104	
R_wheel	110	mm

Table 1 : input parameters of simulated MTF and slanted knife edge.

The main hypothesis is that the objective of the UUT is diffraction limited, we can thus evaluate the PSF of the objective according to x direction with the Airy disk definition of the focused beam at the UUT focal plane:

$$PSF(x) = (\frac{2.J_1(\pi x)}{\pi x})^2 \text{ with } x = \frac{r}{F\#.\lambda} \tag{7}$$

where r = i.δx, i being the step number (i is an integer in the interval [-31;+32]).

The Fast Fourier transform of the PSF is computed to get the objective MTF, MTF_{lens}.

We then calculate the UUT complete MTF as follow:

$$MTF_{UUT\ ref}(\nu) = MTF_{lens}(\nu).MTF_{detector}(\nu) \text{ with} \tag{8}$$

$$MTF_{detector}(\nu) = sinc(\pi.pix_{pitch}.\nu)$$

$MTF_{UUT\ ref}(\nu)$ gives the reference MTF curve which is to be compared to the simulated measured $MTF_{UUT\ simulated}(\nu)$ curve obtained by the slanted knife edge scanning method. The image of a knife edge (ESF(r)) on the UUT focal plane is computed:

$$ESF(r) = FFT^{-1}(FFT(PSF(x)).FFT(H(x)).FFT(\prod(x))) \text{ where} \quad (9)$$

$$H(x) = H(i.\delta x) = 0 \; if \; i < 0 \,; H(i.\delta x) = 1 \; if \; i \geq 0$$

$$\prod(x) = 1 \; if - \frac{pix_{pitch}}{2} \leq x \leq \frac{pix_{pitch}}{2} \; and \prod(x) = 0 \; outside$$

H(x) is a Heaviside function representing the knife edge, ∏(x) represents the pixel.

The LSF and MTF of the UUT are then calculated by:

$$LSF(i.\delta x) = \frac{\partial ESF(i.\delta x)}{\partial r} = \frac{ESF((i+1).\delta x) - ESF(i.\delta x)}{\delta x}$$

$MTF_{UUT\ simulated}(i'.\nu x) = FFT(LSF(i.\delta x))$ with i' natural integer in [0;63] and $\nu x = \frac{f\ UUT}{64.\partial x}$ (cy/mrad) (10)

Using these definitions and equations, the $MTF_{UUT\ simulated}$ and $MTF_{UUT\ ref}$ curves are plotted on the same graph:

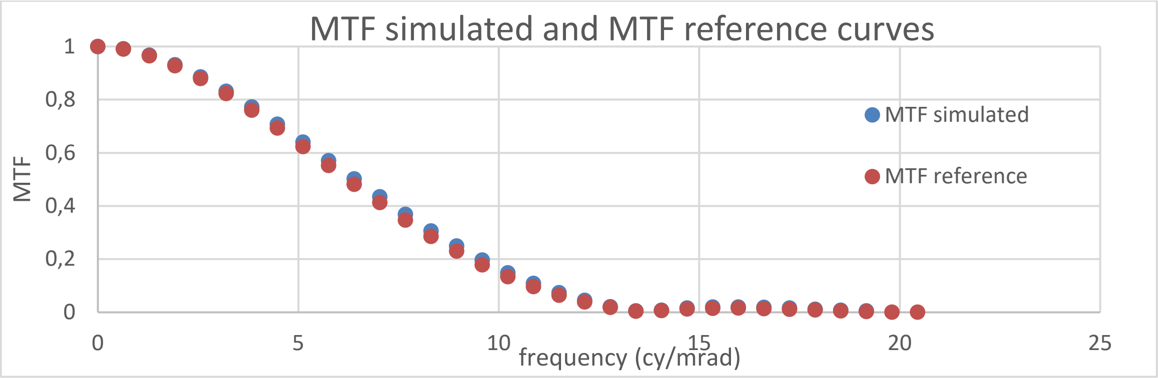


Figure 18 : Reference and simulated MTF curves with Table 1 input parameters

The error curve of the simulation is computed by subtracting the reference MTF values with the simulated MTF values:

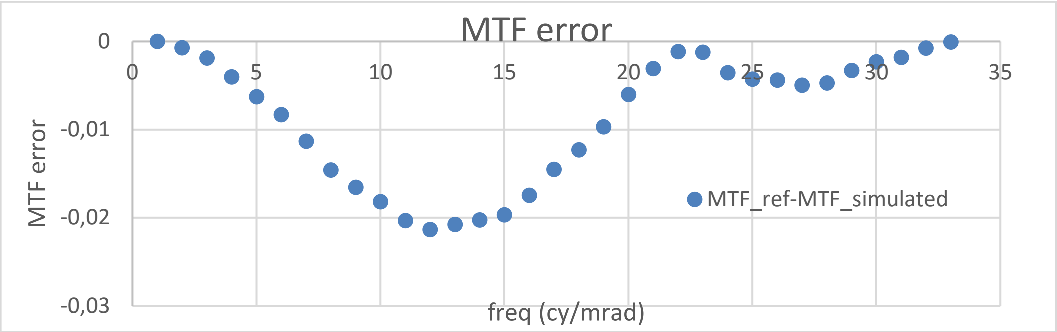


Figure 19 : MTF error evaluation curve

The accuracy of the measurement is the standard deviation of the MTF error curve value σ_{MTF} :

$$\sigma_{MTF} = 0.007 < 1\%$$

This simulation demonstrates that the MTF accuracy is better than 1% thanks to this slanted knife scanning method over the overall frequency bandwidth definition of the MTF curve.

3.3 Measurements and analysis

This method is implemented into INFRATEST software (HGH). In order to validate our simulation, the MTF is measured on the following UUT:

- Edmund Optics objective lens reference #86-410: F# = 8 and F UUT = 100mm
- Visible camera Sony XC-ST50CE used in binned mode (equivalent pixel pitch is twice the datasheet pixel pitch).

The input parameters of the UUT and test bench are:

Parameter name	**Value & unit**	
α	7.125	°
F col	1500	mm
F UUT	100	mm
pix H UUT	17.2	µm
pix V UUT	17.2	µm
Pixel cut off frequency	58.14	cy/mm
Characteristic wavelength of UUT	0.6	µm
F# objective	8	
Cut off frequency objective	208.333333	cy/mm
Number of encoder position for 1 wheel turn	47104	
R_wheel	110	mm

Table 2 : input parameters for MTF measurement of Sony XC-ST50CE camera equipped with Edmund Optic #86-410 lens

The MTF theoretical curve of the lens working at F#=8 and at a field of view of X = 1.49 mm and Y = 0.39mm (initial image position of the knife edge on the camera) is given by the manufacturer.

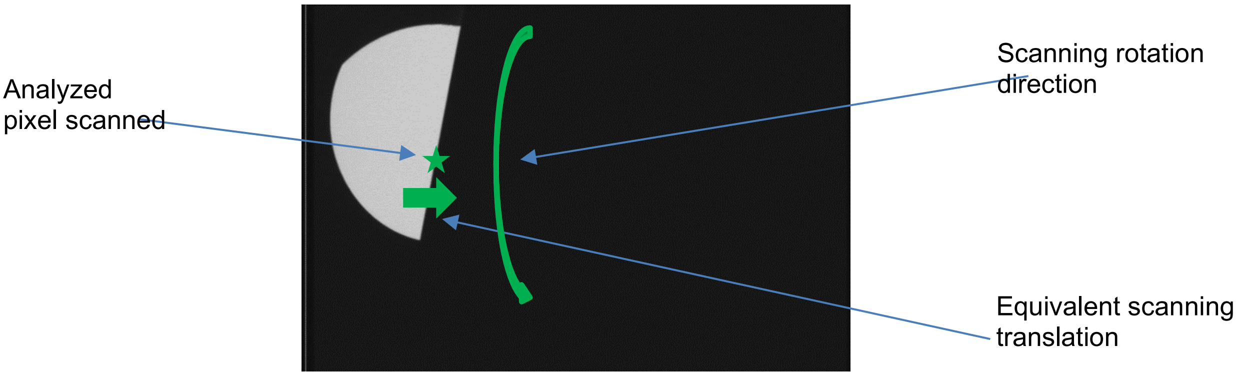


Figure 20 : image example of the knife edge scanning through pixel number (184 ;194) (FOV_X = -1.49mm, FOV_Y = 0.39mm).

By multiplying the theoretical curves with the MTF of the pixel (see (8)) the theoretical MTF of the UUT is calculated and plotted on the same graph as the measured MTF :

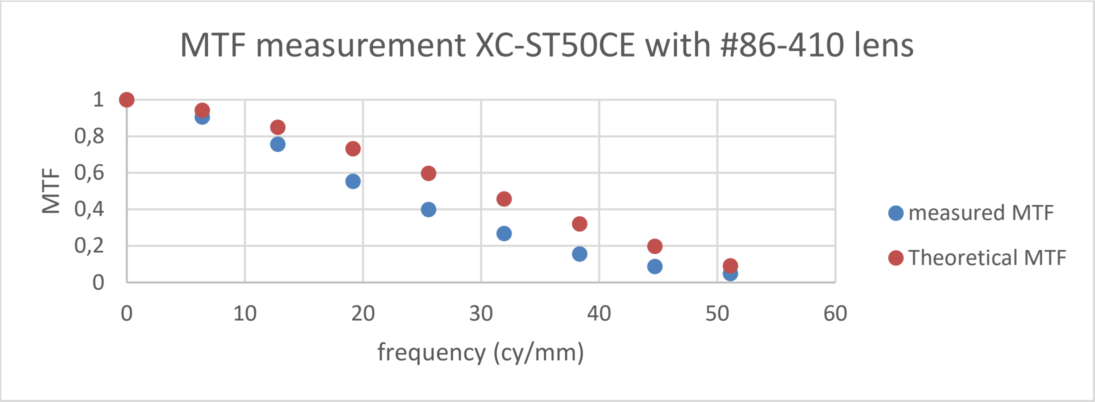


Figure 21 : Measured MTF and theoretical MTF curves of UUT

We can remark the following:

- The curves seem to have the same cut off frequency around 55 cy/mm which is close to the theoretical cut of frequency of the system.
- There is about 20% difference in MTF at Nyquist frequency that can be explained by the following elements:
    - The manufacturer gives theoretical curves of their objectives, these are not measured. The accuracy announced by the supplier is at worst 10% for any frequency.
    - Defocus probably affects the MTF because of the lack in focus precision.

A higher quality and qualified UUT is required in order to make a practical demonstration of the accuracy of MTF slanted knife scanning method.

4. CONCLUSION

The analysis of all pros and cons of all classic MTF methods enabled HGH to identify and develop its own in order to improve its products performance and capabilities.

Simulations demonstrate that the selected algorithm leads to MTF curves and values with 1% accuracy. Nevertheless, first measurements show that a high quality and highly qualified UUT is needed to be able to compare the measurements with accurate data. In order to demonstrate experimentally the 1% accuracy of the method, a highly qualified camera considered as a reference is needed (MTF_{UUT} measured with a precision better than 1%). These kinds of equipment are challenging to find because they need to be qualified on a referenced and valid test bench.

In order to go further in the study, HGH intends to pursue the following developments:

- α angle error: while scanning with the target wheel, there is a slight variation of the α angle linked to the fact that the target wheel turns and doesn't perfectly translate. This error is dependent of the bench and UUT parameters, can be evaluated and taken into account in the algorithm.
- Measured accuracy definition: It would be interesting to find a reference and accurate UUT on which we could compare MTF measurement with the scanning slant knife edge method.

5. REFERENCES

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