Frequency response of optical imaging systems

MATEO MORALES,[1] ESTEBAN VELÁSQUEZ,[1] MARÍA PAULA REY[1,*]

[1]*Physical Sciences Department, EAFIT University, Medellín, Colombia.*
**Corresponding author: mpreyb@eafit.edu.co*

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Resolution and contrast are key parameters in imaging applications. When comparing the performance of optical systems, a commonly used measure is the Modulation Transfer Function (MTF), which is a way to incorporate resolution and contrast into a single specification. We present the experimental and theoretical determination of the MTF of a custom optical setup, including two different microscope objectives. Through the slanted-edge method and a theoretical approach, we determined the behavior of MTF for both coherent and incoherent light. Thus, we were able to compute and compare different MTFs and the frequency response of different optical setups. A thorough analysis indicates that the MTF obtained from using the Fourier transform of the image resulting from a pinhole has greater accuracy and , smoothness, and less experimental hardships compared to the slanted edge method. It was also observed that the processing of an image increases the contrast at low frequencies with enough illumination and at high frequencies in general.

1. THEORETICAL BACKGROUND

When optical designers attempt to compare the performance of optical systems, a commonly used measure is the modulation transfer function (MTF). The MTF of an optical system describes how the image contrast varies with spatial frequency. The MTF of an optical system is the magnitude of its Optical Transfer Function, which is, in turn, a normalized Fourier transform of the point-spread function (PSF) of such system. The computation of the MTF is a mechanism that allows incorporating resolution and contrast data into a single specification [1].

A. Resolution

Resolution is an imaging system's ability to distinguish object detail. It is often expressed in line pairs per millimeter. This measure of line pairs per millimeter (lp/mm) is also known as spatial frequency [1].

B. Contrast/Modulation

Consider normalizing the intensity of a bar target by assigning a maximum value to the white bars and zero value to the black bars. Plotting these values results in a square wave, from which the notion of contrast can be more easily seen (Fig. 1). Contrast or modulation can then be defined as how faithfully the minimum and maximum intensity values are transferred from the object plane to the image plane [1].

The imaging lens, camera sensor, and illumination source are critical in determining the resulting image contrast in imaging applications. The lens contrast is typically defined in terms of the percentage of the object contrast reproduced [1].

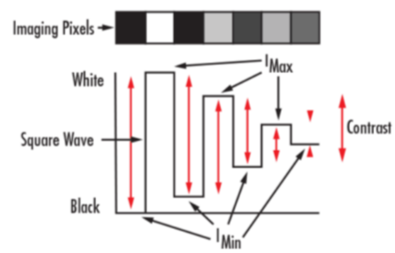

Fig. 1. Contrast expressed as a square wave [1].

The MTF of an optical system is a measurement of its ability to transfer contrast at particular resolutions from the object to the image. In other words, MTF is a way to incorporate resolution and contrast into a single specification. As line spacing decreases (i.e., the frequency increases) on the test target, it becomes increasingly difficult for the lens (or a given optical system) to transfer this decrease in contrast efficiently; as a result, the MTF decreases (Fig. 2) [1].

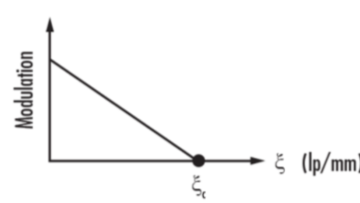

Fig. 2. Ideal MTF for an aberration-free lens with a rectangular aperture [1].

The MTF can be measured in various ways. Using a Siemens Star test chart has one main limitation: the complex numerical processing operations that the recorded images must endure to recover the MTF. Therefore, another evaluation technique arises to characterize the MTF. This technique is based on the so-called slanted-edge method [1].

2. METHODOLOGY

A. Setup

To compute the MTF, a custom setup was built [Fig. 3]. The system was based on a compound microscope, which was equipped with a beam expander, a sample holder with a USAF Test target 1951, two microscope objectives (20X and 10X), a 200mm tube lens, and a CMOS camera.

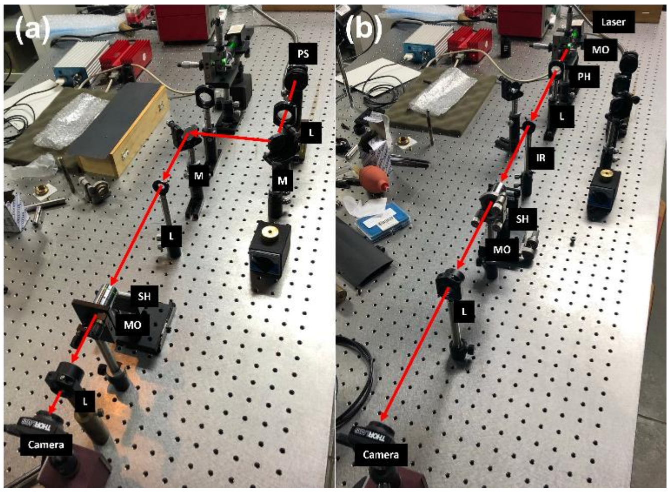

Fig. 3. Optical setup. L, lens; MO, microscope objective; SH, sample holder; MO, microscope objective; IR, iris; M, mirror; PS, polychromatic source.

The following optical instruments were used in this setup:

1. Incoherent light source: Thorlabs OSL2 – High-Intensiry Fiber-Coupled Illuminator.

Numerical aperture: 0.57.
Operating wavelength range: 400-1600nm [1].

2. Coherent light source: B&W Tek BWT-20E/54168 Laser aperture

Wavelength: 532nm.

3. Olympus PLN 10X Microscope objective.

Focal Length: 18.00mm
Numerical aperture: 0.25.
Working distance: 10.6mm [2].

4. Olympus PLN 20X Microscope objective.

Focal Length: 9.00mm
Numerical aperture: 0.40.
Working distance: 1.2mm [3].

5. Thorlabs AC254-200-A Tube Lens, Ø1" Achromatic Doublet.

AR Coating range: 400 - 700 nm.
Focal length = 200 mm [4].

6. Thorlabs DCC1645-HQ Imaging Source CMOS Camera

Pixel size: 3.6 µm, Square.
Imaging area (horizontal x vertical): 4.61 mm x 3.69 mm [5].

Well-focused (and magnified) images were recorded from the USAF Test 1951 for each microscope objective. Then, the slanted edge method was implemented.

B. Slanted Edge Method

The technique of the slanted edge implemented can be described as follows:
First of all, it was necessary to focus an image of a vertically oriented edge (or a horizontal one for the MTF measurement in the other direction) and verify that the slope of the slanted edge with respect to the vertical had a minimum of 2^0 and a maximum of 10^0. Table 1 presents the angles of every edge and their camera configuration.

Table 1. Camera configuration and slanted edge angle in each image.

	Monochromatic source		Polychromatic source	
Value	10X	20X	10X	20X
Angle [°]	5.94	8.96	5.64	6.65
Exposure time [ms]	652.32	2109.01	57.67	2109.01
Frame rate (FPS)	1.22	0.47	5.01	0.47

Later, they were recorded for each microscope objective and light source approximately 50 images of the focused edge, then of the light source (removing the target) and finally of the dark noise (turning off the source beam). After this experimental process the images were averaged, cropped, and converted to gray scale using Python Imaging Library (PIL) and NumPy.

In this way, they were 3 images per source and objective which then were used to compute to different filters. The first filter was implemented simply subtracting the dark noise image from the image of the focused slanted edge. The second filter used the light source image to compute an inversed light source image and subtract it from the edge image just in the white region according to an intensity threshold of 20 (in the 0 to 255 scale).

Finally, to compute the MTF function of the image without processing and with each filter the program MTF Mapper was implemented according to your guide [6] in setting cycles per pixel and manual edge selection.

C. Theoretical Approach (Fourier's Theory)

With the objective of achieving a theoretical approach of the MTF using Fourier's theory, it was necessary to locate a pinhole at a sample plane and try to accurately locate the objective to record an image of the impulse response function of the system (PSF). However, due to the difficulty of this task, it was only possible to focus the 20X objective.

After averaging the 50 images taken and cropping the resulting image, the Fourier transform was computed to obtain the horizontal and vertical frequency response profiles of the system from its magnitude by normalizing their axes.

Finally, to analyze the MTF functions obtained it was discussed the differences (qualitatively and quantitatively) between the two methods implemented, which objective yielded the best MTF and the relations of these results with theory.

3. RESULTS

A. Slanted Edge Method

The USAF Test images taken for each microscope objective with polychromatic light are shown in Fig. 4. It can be noted that the sharpness decreases with higher frequency lines and with lower illumination.

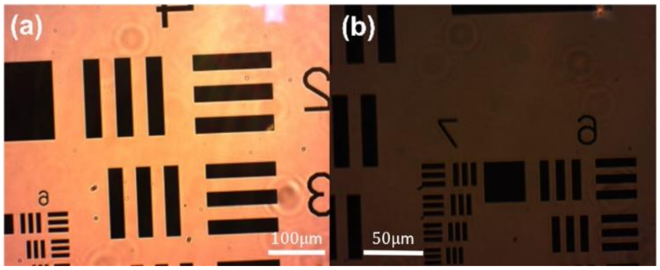

Fig 4. Focused test USAF with (a) the 10X objective and (b) with the 20X objective.

The differently processed images taken with the 10x objective are viewed in Fig. 5, where the dark noise is removed in the second column of the image; and the white noise or spots from the white part are also removed, as it can be seen in the third column of the image.

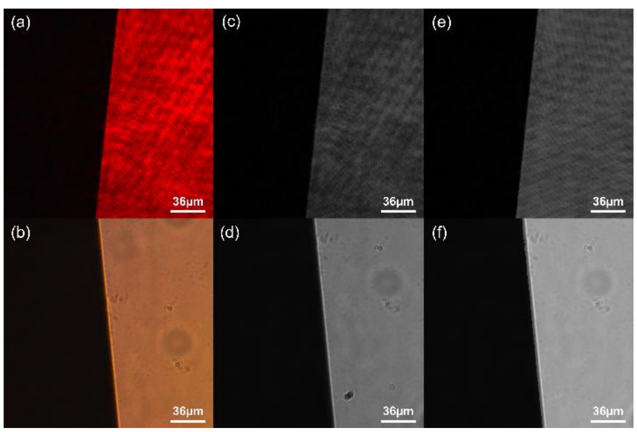

Fig. 5. Images obtained with the 10X objective with: (a) monochromatic source and without processing; (b) monochromatic source and filtering dark noise; (c) monochromatic source and filtering dark and white noise; (d) polychromatic source and without processing; (e) polychromatic source and filtering dark noise; (f) polychromatic source and filtering dark and white noise.

In the same way, the differently processed images taken with the 20x objective are viewed in Fig. 6, where the dark noise is removed in the second column of the image; and the white noise or spots from the white part are also removed, as it can be seen in the third column of the image.

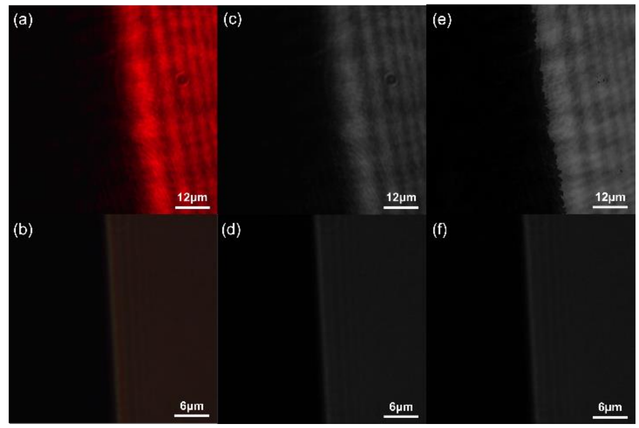

Fig. 6. Images obtained with the 20X objective with: (a) monochromatic source and without processing; (b) monochromatic source and filtering dark noise; (c) monochromatic source and filtering dark and white noise; (d) polychromatic source and without processing; (e) polychromatic source and filtering dark noise; (f) polychromatic source and filtering dark and white noise.

B. Theoretical Approach (Fourier's Theory)

The PSF of the system or the output image of the pinhole and its respective Fourier transform in the right can are illustrated in Fig. 7. Where the Fourier transformation is done for monochromatic and polychromatic light.

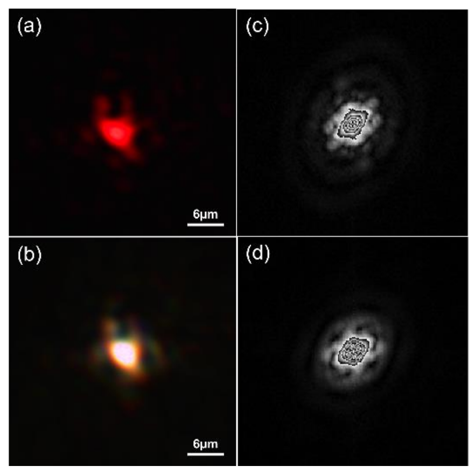

Fig 7. Experimental PSF of the 20X objective with monochromatic and polychromatic ((a) and (b)) and fast Fourier transform of each PSF ((c) and (d)).

C. MTF analysis

The monochromatic experimental and theoretical MTF comparisons are shown in Fig. 8. In which the filters added increase the contrast at high frequencies. It can also be seen that due to the high difficulty of aligning the pinhole, the beam, and the center of the image there is a fuzzy contrast at low frequencies.

The polychromatic experimental and theoretical MTF are illustrated in Fig. 9. In this figure the processing doesn't affect much the contrast at high frequencies because the illumination was lower in these images.

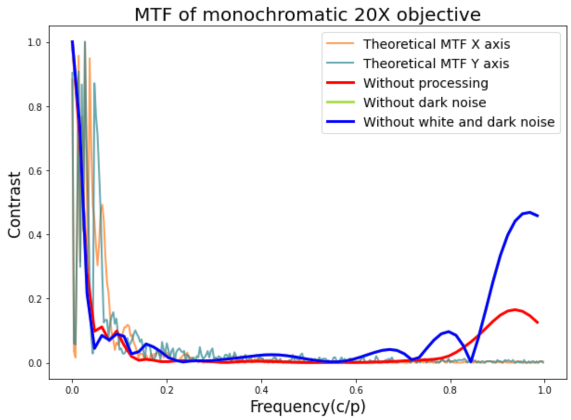

Fig 8. Experimental and theoretical MTF of monochromatic 20x objective

In addition, according to figure 9 theoretical MTF is much lower in general than the experimental in this case, and it's also fuzzy since the same problem of aligning persists. It can also be seen that the MTF is much higher than the monochromatic MTF shown in Fig. 8.

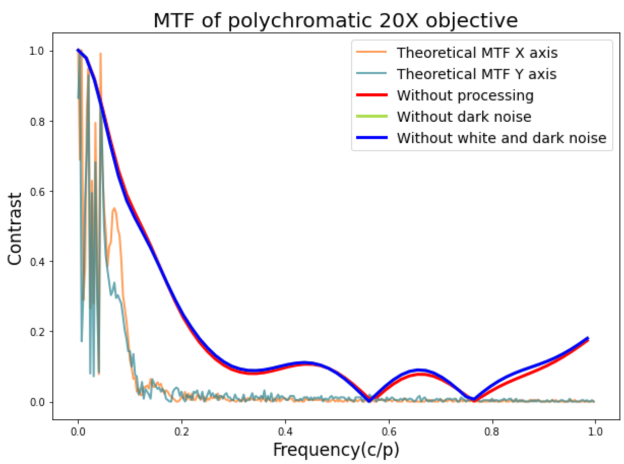

Fig 9. Experimental and theoretical MTF of polychromatic 20x objective.

The polychromatic and monochromatic MTF comparison of the 10x objective can be viewed in Fig. 10. In here the polychromatic MTFs are in general higher than those of the monochromatic and even more with those of the 20x objective seen in the dot dash red line, except maybe for the high frequencies, that the 20x is a bit higher. It can also be indicated by the figure that with enough illumination, the contrast at low frequencies increased with the filters applied; specially here in 10x objective that the area illuminated is considerably more than the 20x objective, as expected from the theory with the change of numerical aperture [7] and because of that it can be said that the MTF of the 10X objective is better. This can be easily verified by observing how the contrast for very close lines in the USAF test presents less contrast for the 20X objective [Fig. 4(b)].

The large differences between the polychromatic and monochromatic MTFs can be explained by diffraction theory, since diffraction depends on the wavelength, and because difficulties found in the process of obtaining a uniformly distributed spot. It can be also said that the focusing of a polychromatic image was easier than that of the monochromatic, creating some error in the real contrast of the monochromatic images.

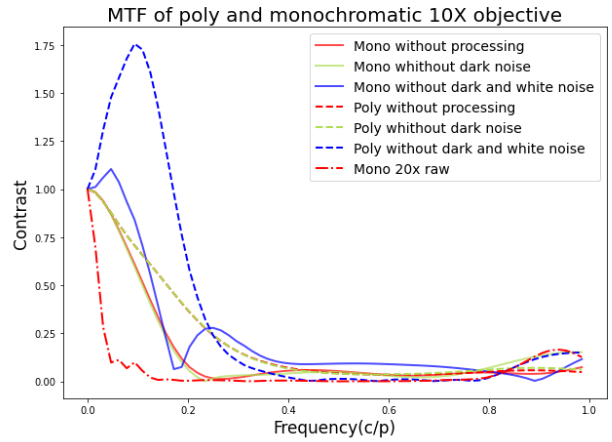

Fig 10. Experimental MTF comparison of poly and mono chromatic 10x objective.

4. CONCLUSIONS

- The MTF can be experimentally measured and calculated using the Fourier transform of the image resulting from a pinhole and with the slanted edge method, with greater accuracy and smoothness and with less experimental hardships from the latter.
- The processing of an image increases the contrast at low frequencies with enough illumination and at high frequencies in general.
- The contrast of and objective decreases in general with the increase of frequency except for the 20x at higher frequencies.
- The MTF is proportional to the numerical aperture of an objective.
- The MTF obtained with polychromatic light has better results in contrast.

Disclosures. The authors declare no conflicts of interest.

Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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