Broad-band optical test bench (OPTISHOP) to measure MTF and transmittance of visible and IR optical components

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ABSTRACT

CI Systems has developed a new cost effective and modular Optical Test Bench to measure Modulation Transfer Function (MTF) and transmittance of optical components in the Visible/Near Infrared (0.4-1.7 microns) and infrared (3 to 14 microns) spectral ranges (the OPTISHOP system). The optical design concept of the system allows the user to switch from MTF (on- and off-axis) to transmittance measurements, without need of optical alignment by the user. In addition, broad band sources are used for illumination, so that these optical properties can be measured in the whole relevant wavelength range of the components to be tested (usually visible and/or near infrared separately from the infrared range). Other lens measurements such as effective focal length can be made. Back focal length, distortion and field curvature are being developed.

The system is based on the standard and proven CTS (Collimator Test System) product line of CI, which is made of reflective optics for wide wavelength coverage, and it is ruggedly built for use in the laboratory, production line or maintenance depot. An advantage of the CTS configuration is that the source-collimator assembly is enclosed in a robust mechanical envelope, which prevents accidental misalignements and breakage, optical misalignments due to environment temperature drifts, soiling of the optics, and easier system transportation.

The system is described here, including calibration and validation techniques.

Keywords: Optical testing, Modulation Transfer Function measurements, Lens Transmittance, MTF of Infrared and Visible components

1. INTRODUCTION

Optical component testing is an old and well known field of optical engineering. This is the mastering of the techniques developed in order to test a produced optical component and compare its expected with its actual performance. As examples of existing literature in this field we mention here a chapter of a classic book[1] and a more recent tutorial booklet[2]. This literature is in no way exhaustive, but it gives the reader at least a basic understanding and knowledge of the relevant physical parameters to be measured and the most popular and practical techniques used to measure them.

The testing techniques can be classified into two main categories: i) assessments of wavefront shapes of monochromatic light propagating through the component(s) to be tested using interferometric methods, and ii) analysis of the intensity distribution of the image of special collimated polychromatic patterns produced by the lens(es) to be tested. As usual each technique has its own practical advantages and disadvantages. The optical component producer or user can then select the most appropriate and optimal technique for the task at hand in each specific case.

The purpose of this paper is to describe work recently performed at CI Systems to build a multipurpose lens testing system with several advantages over similar existing systems. The tests that the system is designed to provide are of the second type (image plane intensity distribution). Its advantages are geared to practical convenience from the point of view of the user. In particular these advantages are: i) a closed rugged system suitable for R&D in the laboratory, production line or maintenance depot, ii) the possibility of measuring polychromatic MTF and transmittance with the same hardware without realignments, and iii) all reflective optics for use in the visible, near infrared and infrared ranges (0.4 to 14 microns) with the same hardware.

In section 2 a system description is given, mentioning some design considerations and advantages and user interface screens. Some of the most important measurement procedures will also become clear. In section 3 examples of measurements are shown with validation results and mention of the typical achievable accuracy. Section 4 is devoted to a short summary and conclusions.

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2. SYSTEM DESCRIPTION

2.1. MTF mathematical relation to Line Spread Function (LSF)

Section 4.2 of reference 2 clearly summarizes the relation between the MTF as function of spatial frequency ξ in cycles/mm conjugate to the x direction and the LSF as function of the same direction x. Equation (4.9) is the basic relation:

$$|\mathcal{F}\,[LSF(x)]| = MTF(\xi,\eta)_{\eta=0} \quad (1)$$

where the symbol $\mathcal{F}$ stands for Fourier Transform.

In equation (1) LSF(x) is the intensity of light imaged by the lens under test on its focal plane, due to a collimated slit pattern parallel to the vertical y direction, x is the horizontal direction and ξ is the spatial frequency coordinate conjugate to x. The second coordinate η (the spatial frequency coordinate conjugate to y) of the MTF in equation (1) is taken as 0 since along the slit length the light intensity is uniform and therefore the MTF (analogous Fourier Transform in the y direction) is different from 0 only at $\eta=0$. Analogous results for MTF(0,η) can be obtained by measuring the LSF(y) with the slit parallel to the x direction.

The OPTISHOP system is designed to provide a slit pattern collimated beam in the wavelength range in question and the means to measure the LSF(x) function of the lens under test. The optical system used to project this collimated beam has large exit pupil and long focal length, it is very close to diffraction limit and its aberrations do not contribute an appreciable blur to the slit image. The system is also designed with some selectable parameters such as slit width, source intensity, etc. so that it can be used for different lenses. It has additional capabilities such as on-axis detector-slit scans for MTF measurements in both the horizontal and vertical directions, and off-axis only in the horizontal direction. In the next section the optical layout and other important characteristics for MTF are shown.

2.2. Optical layout for MTF measurements

Figure 1 shows the optical layout of the system and figure 2 shows the way the actual system looks when assembled.

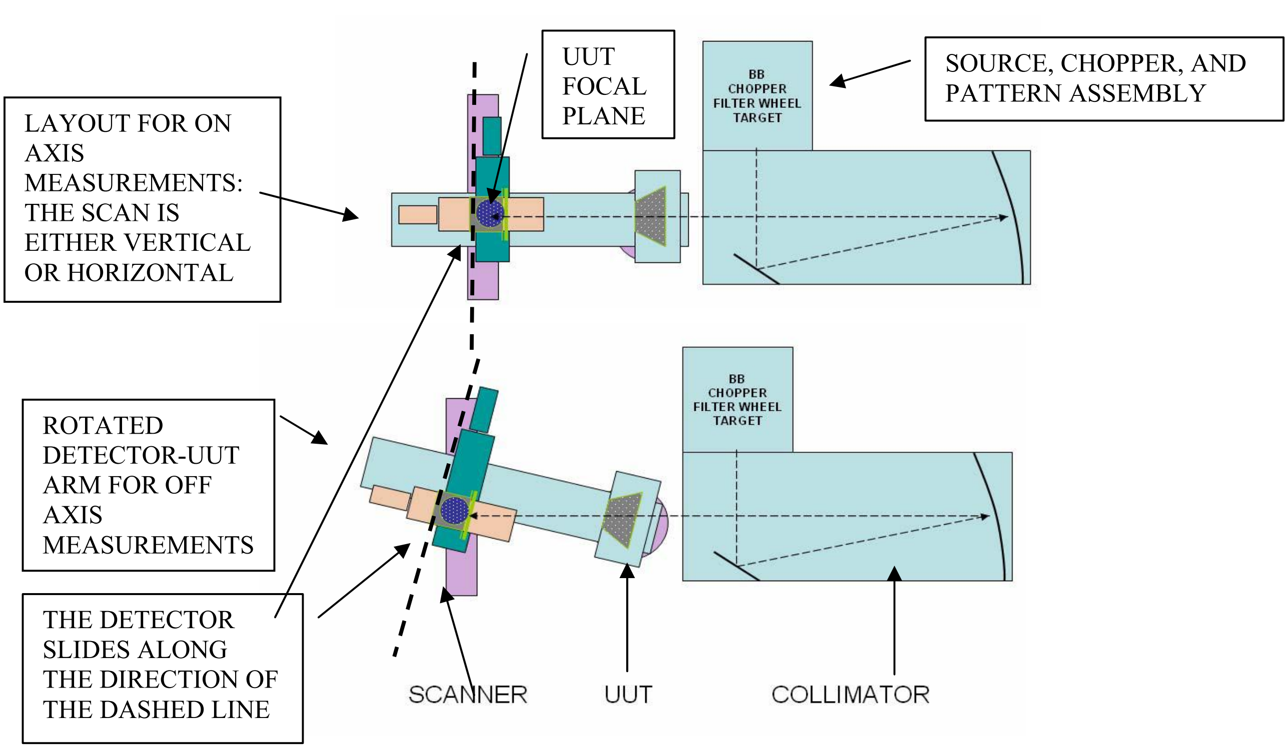

Figure 1: Optical layout diagram of the assembled OPTISHOP system. The lower diagram shows the system when the detector-UUT arm is rotated to perform off-axis measurements. The rotation is around a vertical axis going through the lens to be tested.

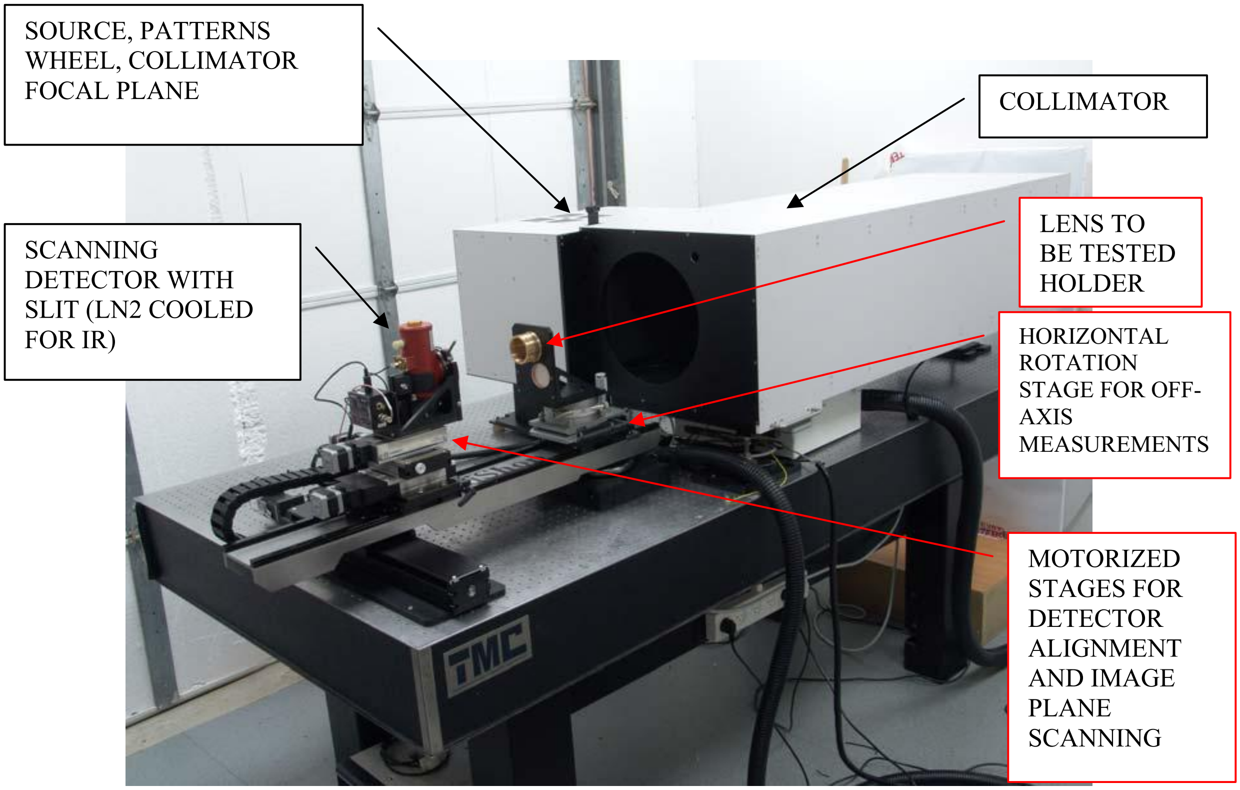

Figure 2: The assembled OPTISHOP system.

The collimator is a large 10” clear aperture diffraction limited, off-axis Newtonian reflective parabolic mirror of F#7. The detectors for infrared lenses are single element liquid nitrogen cooled InSb or MCT, sensitive in the wavelength ranges of 3 to 5 μ and 8 to 14 μ respectively. The slit pattern, aligned in the vertical direction, is collimated and projected onto the lens under test, which is mounted on the holder in figure 2: the lens under test forms an image of the collimated slit pattern on its focal plane. The detector assembly includes a slit in front of the detector window, parallel to the slit pattern direction, which can be accurately positioned on this focal plane. The width of the slit in the detector assembly is at least one order of magnitude smaller than the width of the slit image on the UUT focal plane, so that the slit image can be sampled horizontally by at least ten data points, to form the LSF(x) function.

The parameter ranges for lenses that can be tested are: 1”-10” for the diameter, 1.3 and higher for the F# of 3-5μ lenses, 1 and higher for the F# of 8-12μ lenses, and 1/2-20”. for the back focal length (BFL). The movement range of the detector with respect to its central position on the axis perpendicular to the optical axis of the lens to be tested determines the limit of off-axis testing that can be performed: this range is ±2”. Given a slit pattern width on the collimator focal plane, the ratio of lens to collimator focal lengths determines the slit image width on the lens focal plane: so, similarly to the detector slit width, the detector assembly step size can be controlled to small enough steps so that enough LSF(x) samples are collected during the scan. The minimum step size is 0.1μ. The available slit width range on the collimator focal plane is 20-100μ and in front of the detector is 5-10μ. The minimum angular step size for off-axis measurement is 3.6 sec.

Figure 3 shows a diagram of the image plane and examples of measurement parameters.

Let us work out some basic measurement parameters for two very popular cases: a 3-5μ lens and an 8-12μ lens, both with F#=5. In the former case we take λ=4 microns and in the latter λ=10 microns as representative wavelengths respectively. Since the lenses are in the best case diffraction limited, it is enough to measure the MTF function for spatial frequencies up to the diffraction limit cut-off frequency. This is because the diffraction limit cut-off frequency is the highest frequency for which the MTF $\neq$ 0.

We have, according to equation (1.27) of reference 2:

$$\xi_{4,\text{cut-off}} = 1/(\lambda F\#) = 1/20\ \mu^{-1} = 50\ \text{mm}^{-1} \text{ for } \lambda=4\mu \quad (2)$$

and

$\xi_{10,cut\text{-}off} = 1/(\lambda F\#) = 1/50\ \mu^{-1} = 20\ mm^{-1}$ for λ=10μ (3)

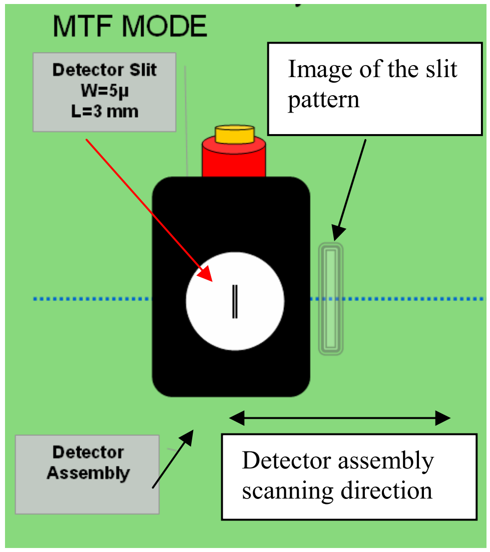

Figure 3: Diagrammatic view of the focal plane of the lens to be tested.

From Fourier Transform theory we know that: i) the step size Δx of the sampling in the x domain must be not more than $1/(2\xi_{cut\text{-}off})$ (Nyquist condition), and ii) the sampling range in the x domain must be not less than the inverse of the desired frequency resolution of the measurement.

These two conditions dictate the following, from (2) and (3):

$\Delta x \leq 1/100$ mm = 10 μ for λ=4μ (4)

$\Delta x \leq 1/40$ mm = 25 μ for λ=10μ, (5)

and for the total scan range x_{max} of the detector assembly in the x direction on the focal plane:

$x_{4,max} = n / \xi_{4,cut\text{-}off} = 0.02{*}n$ (mm) for λ=4μ (6)

and

$x_{10,max} = n / \xi_{10,cut\text{-}off} = 0.05{*}n$ (mm) for λ=10μ (7)

where n is the number of points in the ξ domain at which the MTF function is measured and $\xi_{cut\text{-}off}/n$ is the frequency resolution of the MTF measurement. For example for n=10, we have:

$x_{4,max}$ = 200 μ for λ=4μ (8)

and

$x_{10,max}$ = 500 μ for λ=10μ (9)

In both cases of radiation wavelengths 4 and 10 μ, by dividing equations (8) and (9) by (4) and (5) respectively, we get at least 20 measurement points or samples for the LSF(x) in the x domain.

According to figure 1, an off-axis MTF measurement is done by rotating the detector arm by the desired angle around a vertical axis through the lens to be tested (UUT). The direction of movement of the detector assembly is perpendicular to the lens optical axis, as shown in the figure, in both on-axis and off-axis cases.

2.3. Effective Focal Length (EFL) measurements

The effective focal length of a lens is measured with the OPTISHOP system simply by measuring the distance d between the images of two collimated vertical slit patterns angularly shifted with respect to each other, formed by the lens to be tested. If α is the angular distance between these two sources and EFL is the lens effective focal length, the relation is:

$$EFL = d/\tan\alpha \qquad (10)$$

α is the rotation angle of figure 1 and it is controlled through the rotation stage and encoder on which the lens holder is mounted. d is measured by scanning the detector assembly: the distance between the two positions of maximum signal is known through the translation stage and encoder on which the assembly is mounted.

2.4. Through Focus MTF measurements

A defocus MTF function is useful in case the tolerance of a lens or lens group position alignment is needed with respect to other system reference positions. In the OPTISHOP system the Through-Focus MTF is measured by first measuring the LSF(x) function at different positions of the detector assembly along the optical axis of the lens to be tested (z coordinate) and then by Fourier transforming the various LSF(x). The MTF values corresponding to a desired spatial frequency value ξ is then plotted as function of the coordinate z. For z=0 the corresponding MTF value is the one measured on the focal plane of the UUT.

2.5. Lens transmittance measurements

Figure 4 shows the optical layout used for transmittance measurements.

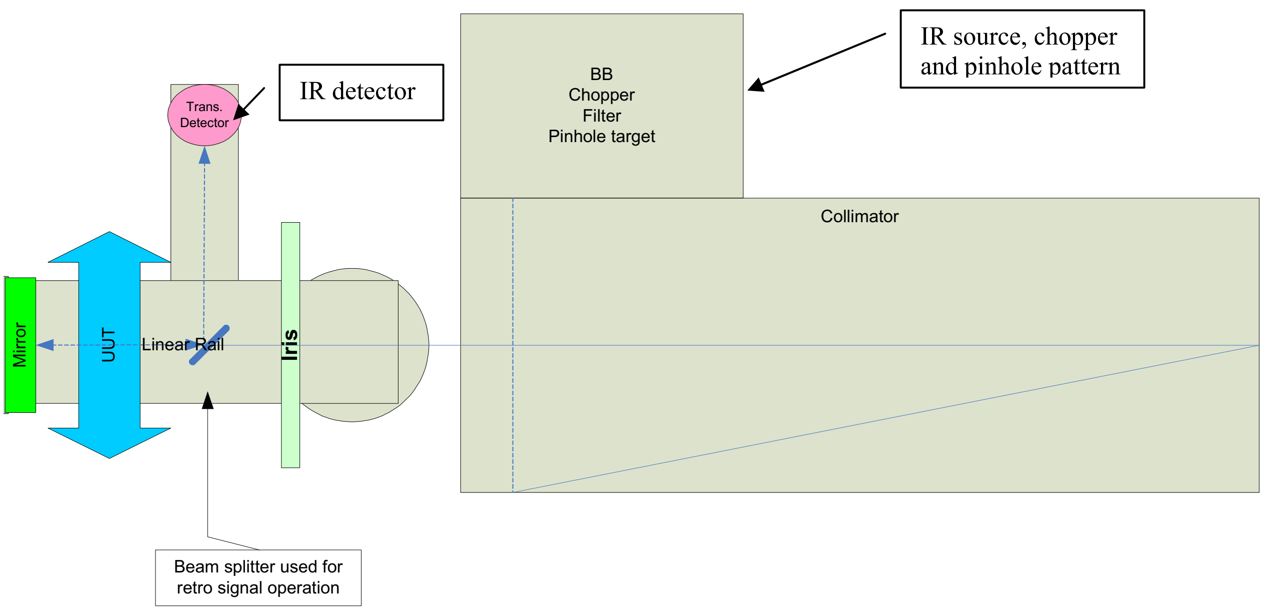

Figure 4: OPTISHOP optical layout for transmittance measurements. The collimated radiation from the source goes through an iris to match the illumination cross section with the lens diameter, then through a beamsplitter, through the UUT, it is reflected by a high reflectance mirror, back to the UUT and it is finally reflected by the beamsplitter to the IR detector. The reference measurement is done without the UUT in the path.

The transmittance concept is based on measuring the intensity of the beam from a collimated pinhole pattern being transmitted through the lens (UUT) in a double pass configuration. The beam is reflected back to itself by a mirror (on the left side of the figure) and measured by the IR detector. The signal is compared with the analogous signal in the absence of the UUT: the ratio of the two is equal to the square of the lens transmittance. If s is the signal measured by the detector when the lens is in place and s_0 is the signal measured without any lens in the path, then

$$s/s_0 = \tau^2 \text{ and} \qquad (11)$$

where τ is the transmittance through the lens. τ appears squared in (11) because of the double pass. Taking the square root of (11),

$\tau = (s/s_0)^{1/2}$ (12)

2.6. User interface

Figure 5 shows a user interface screen for the operation and control of the system functions.

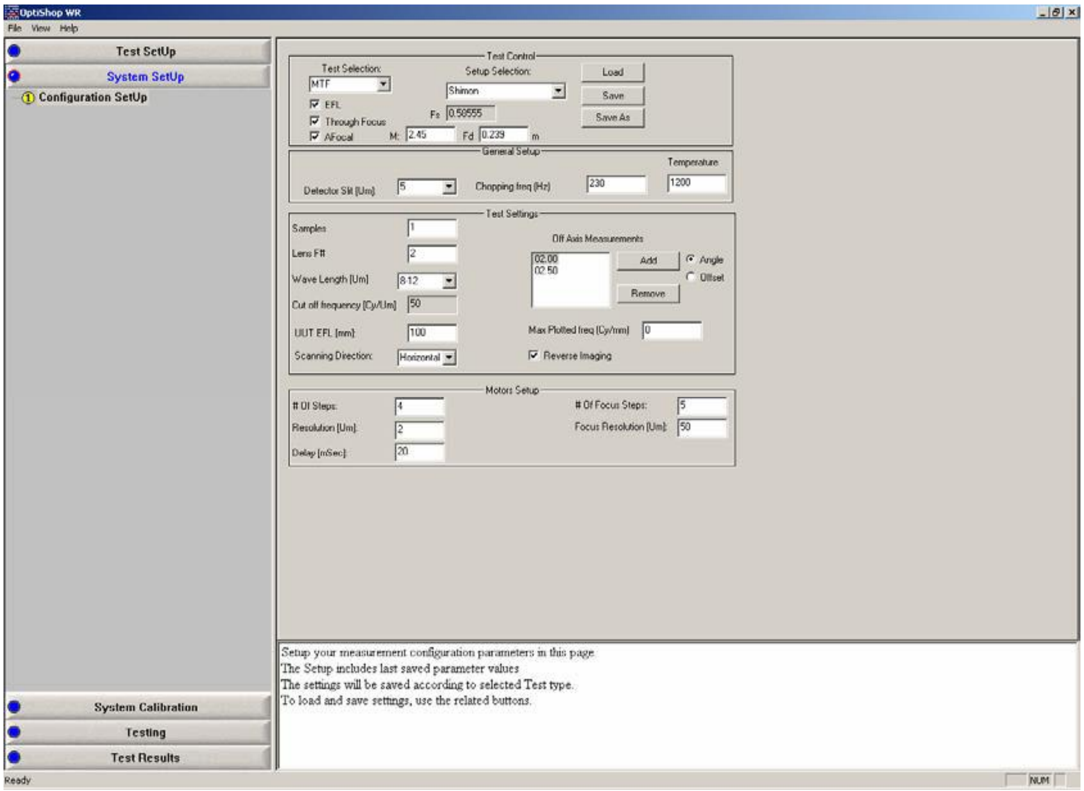

Figure 5: The main screen of the OPTISHOP system user interface, in which the measurement parameters are set.

3. SYSTEM VALIDATION AND EXAMPLES OF MEASUREMENTS

3.1. System validation

It is important to convince ourselves that the measurement of a lens MTF using the OPTISHOP gives correct and reliable results. There is no world recognized standard MTF system or method known to us, that we could compare our results with for validation. The MTF curve, calculated on the basis of the measured LSF, PSF (Point Spread Function) or ESF (Edge Spread Function) is indirectly measured. Therefore, comparisons with other MTF measuring systems may be inconclusive as to the correctness of the OPTISHOP results, chiefly because of the possibility of errors in the algorithm coding software of any system, ours and/or the one selected for comparison. The question then arises as to how we can prove that the method and the algorithms used in the system give the correct results.

The MTF of an optical system can be measured by independent interferometric methods. For example, see references 4, 5, and 6 which show that MTF can be measured using lateral shear interferometry, among others. So, one way of validation is to have such interferometric measurement done on the same lens as measured by OPTISHOP. However, the following alternative, for validation purposes, is simpler because it does not require additional instrumentation. In addition, interferometric methods are done with monochromatic light, and therefore are not exactly equivalent to a polychromatic MTF measurement, such as provided by OPTISHOP.

Diffraction limit, for any lens, sets an upper bound for its modulation transfer at any spatial frequency. The MTF(ξ) function of a diffraction limited lens is known exactly, analytically or otherwise, when measured in different situations: i) on the focal plane, ii) in defocus and iii) with a central obscuration[3]. This MTF on the focal plane depends only on the wavelength of the measurement and on the lens' F#, and on no other parameter; in defocus it depends also on the amount of defocus and in the third case on the amount of central obscuration. As a result, any significant deviation of the measured MTF from the theoretical MTF of such lens in the different situations mentioned above must derive from a flaw in the measurement system. Conversely, if the system gives MTF results which are satisfyingly close to the known curves in several of the above situations (in focus and defocus and/or with central obscuration), then the OPTISHOP system can be considered to measure correctly.

In other words, a diffraction limited lens measured in defocus for example, can be considered a simulation of a non diffraction limited lens with a known MTF(ξ) function, provided its defocus is known, for the validation purpose we are looking for.

3.2. Examples of measurements

Figures 6 and 7 show the MTF measurement results obtained with the OPTISHOP system of two lenses, one in the 3-5 μ and one in the 8-12 μ range. The 3-5 μ lens is not diffraction limited while the 8-12 μ lens is close to it. Therefore the MTF measurement result of the former, knowing its parameters, is compared with the lens design prediction by CODE V, while the latter is compared with the diffraction-limited MTF curve.

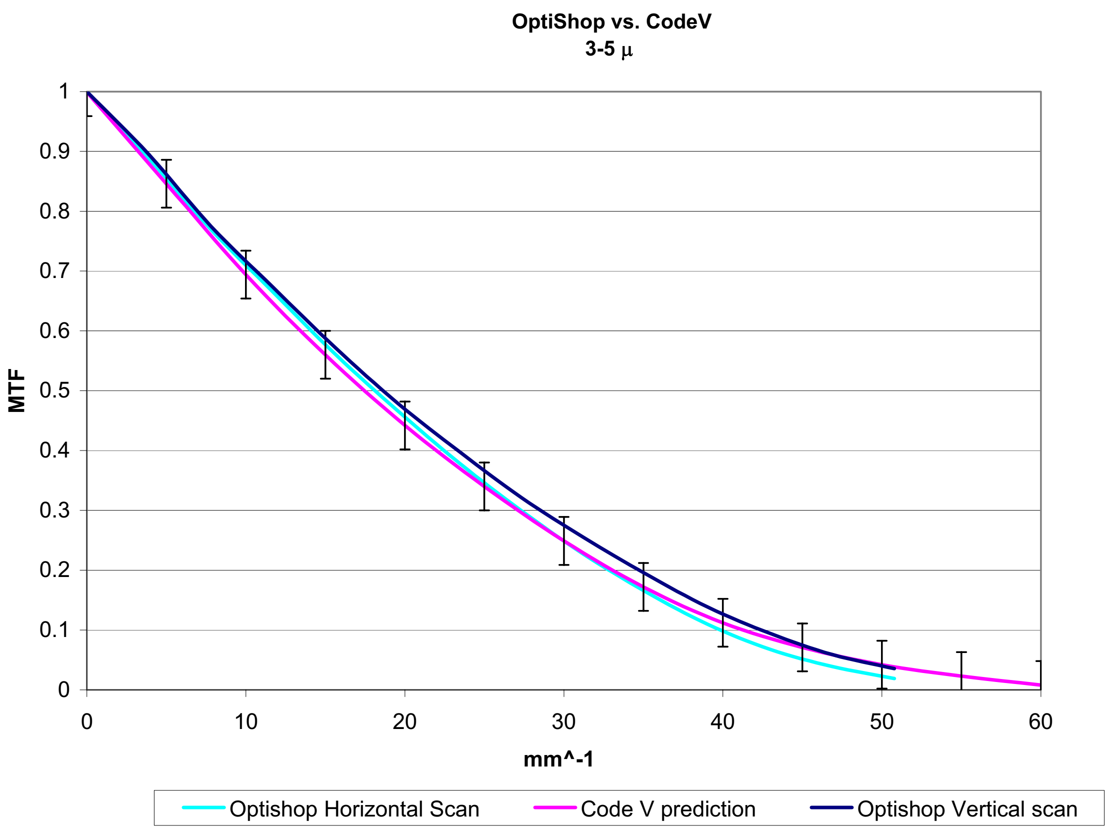

Figure 6: On-axis MTF measurement with the OPTISHOP system of a 3-5μ lens (Si/Ge doublet not diffraction limited) versus CODE V prediction. The lens is an EFL 250 mm., entrance pupil 48 mm. diameter. Deviations are ~±4%.

In figure 6 good agreement between the CODE V prediction and the measurement results is shown within a +- 4% error bar.

In figure 7 good agreement between the diffraction-limited MTF curve and the measurement results is shown within a +- 3% error bar. Both figures 6 and 7 show validation of the OPTISHOP system to a certain extent. However, additional measurements such as in the situations suggested in section 3.1 above are needed and are planned in the near future.

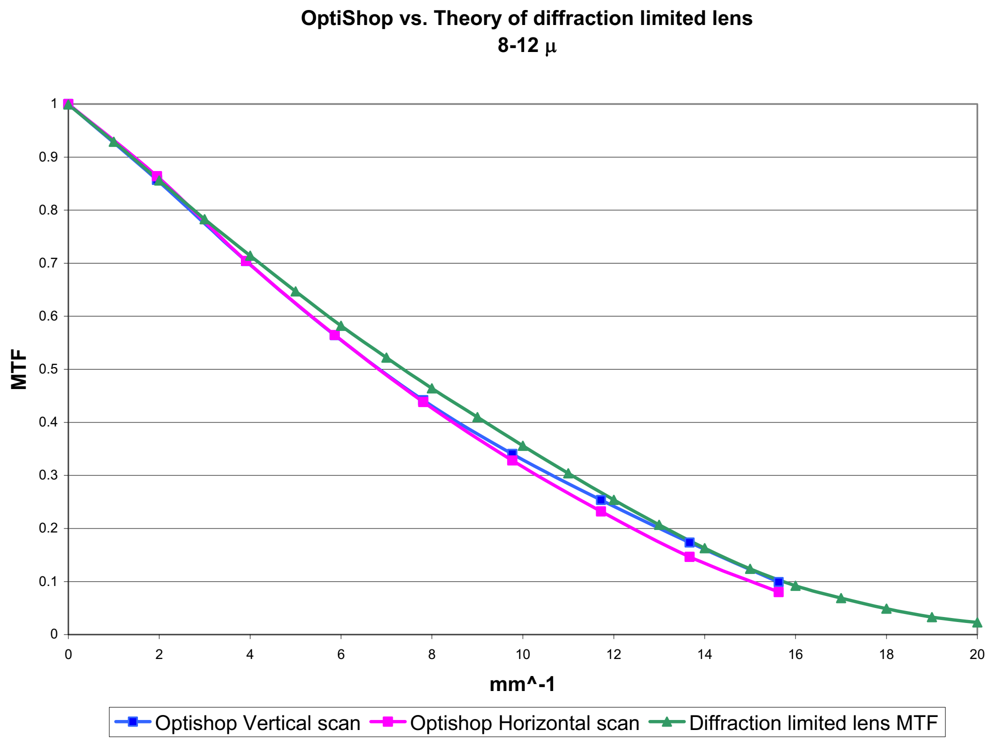

Figure 7: On-axis MTF measurement with the OPTISHOP system of an 8-12μ lens (Ge singlet close to diffraction limit) versus theoretical diffraction-limited MTF curve. The lens is an EFL 252 mm., entrance pupil 48 mm. Deviations are ~±3%.

4. CONCLUSIONS

We have shown work recently performed at CI to develop a new MTF and transmittance measurement system for lens and lens groups called OPTISHOP. We have shown the basic design principles of such system, its advantages, measurement results and validation concept. The most important advantages of the system are: i) the capability of measuring MTF and transmittance with the same hardware without cumbersome optical alignments, ii) wide band coverage for lenses in the 0.4 to 14μ range, and iii) a rugged construction and enclosure for environmental shielding and easy transportation.

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