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An Instrument for Measuring the Modulation Transfer Functions of Low Power Telescopes and Telemicroscopes

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ABSTRACT

An instrument using an electro-optical Fourier method for measuring the modulation transfer function (MTF) of low power telescopes and telemicroscopes is described. Because these devices are afocal, or nearly so, relay optics are needed to form real images at the detection section of the apparatus. The system is capable of measuring the MTF in monochromatic and white light, at any target azimuth, across the field of view, and through focus. The target system contains 14 square-wave gratings with spatial frequencies that range from 2.5 to 156 cpd. Images of these gratings are scanned across a slit. The output data are fed to a first-order recursive digital Butterworth bandpass filter for MTF analysis. The apparatus is diffraction limited at f/31.4. Therefore, it negligibly affects the measurement of the MTF of telescopes and telemicroscopes tested with exit pupils of up to 6.4 mm.

Key Words: modulation transfer function, low power telescopes, optical testing

This laboratory recently reported on the resolving power of telescopes prescribed by low vision clinicians.[1] Resolving power is a subjective measurement of optical quality. A more complete and objective method of image evaluation is provided by the MTF. The design and theory of instruments for measuring the MTF of focal and afocal optical systems, utilizing a large variety of methods, has been well documented.[2-16] This paper describes a MTF apparatus for testing visual instruments that we designed and built at the Schnurmacher Institute for Vision Research.

DESIGN GOALS

Our goals were to be able to measure the MTF of low vision afocal devices of up to 8 power, to a spatial frequency of 20 cpd in image space. Generally, 8× is the highest magnification that is practical, given the amplification of hand and head tremors in the image. The corresponding spatial frequency of 20 cpd was chosen because low vision observers are unlikely to utilize higher frequency information effectively. Higher spatial frequencies can be measured with lower power devices.

Additional requirements were the ability to measure MTF's in monochromatic or white light, at any target azimuth, across the full field of view of the device, and through focus.

We also wanted the apparatus to be flexible enough to test telescopes that are afocal in object and image space, telemicroscopes that are afocal in image space but have finite working distances, and focal lenses.

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DESCRIPTION OF APPARATUS

The MTF apparatus comprises a target system, an adjustable optical mount, a detector system, and processing electronics all mounted on a vibration-isolated table; see Figs. 1 and 2.

The target system consists of 14 high contrast square-wave patterns on Kodak LPD-4 film that increase approximately logarithmically in spatial frequency from 2.5 to 156 cpd. The film is wrapped around a drum with 14 corresponding windows that is driven by a 20 rpm synchronous motor. The resulting temporal frequencies range from 22 to 1379 Hz, and are proportional to the spatial frequencies shown in Table 1. The drum is rotatable about an azimuth axis that tilts the targets through 180°, with detents at 0, 45, 90, and 135°; see Fig. 3.

The illuminator, shown in Fig. 4, is located inside the drum and diffusely back-illuminates the film transparencies. Appropriate filters provide either a narrow passband peaked at 550 nm

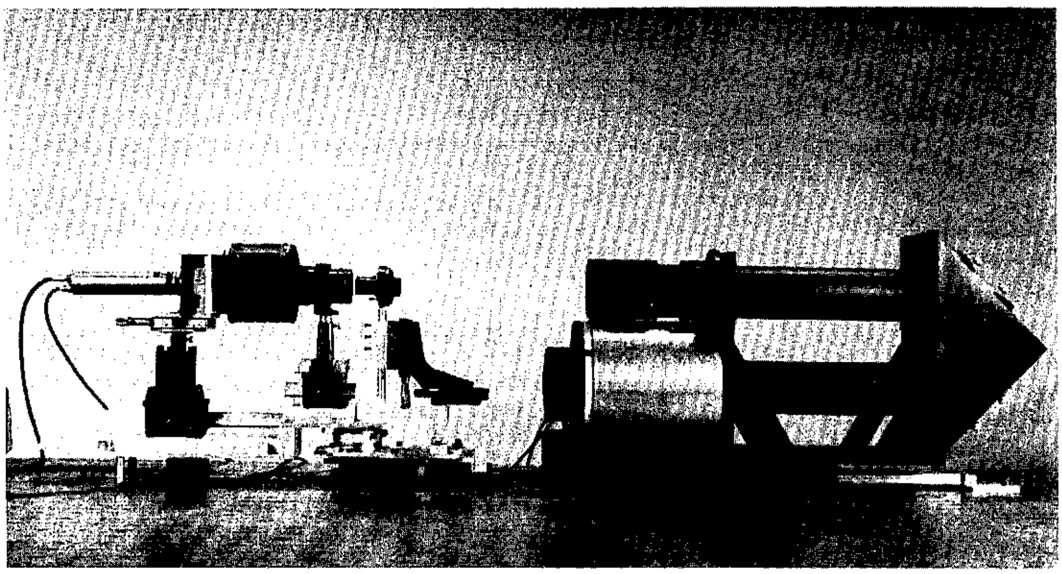

FIG. 1. The MTF apparatus.

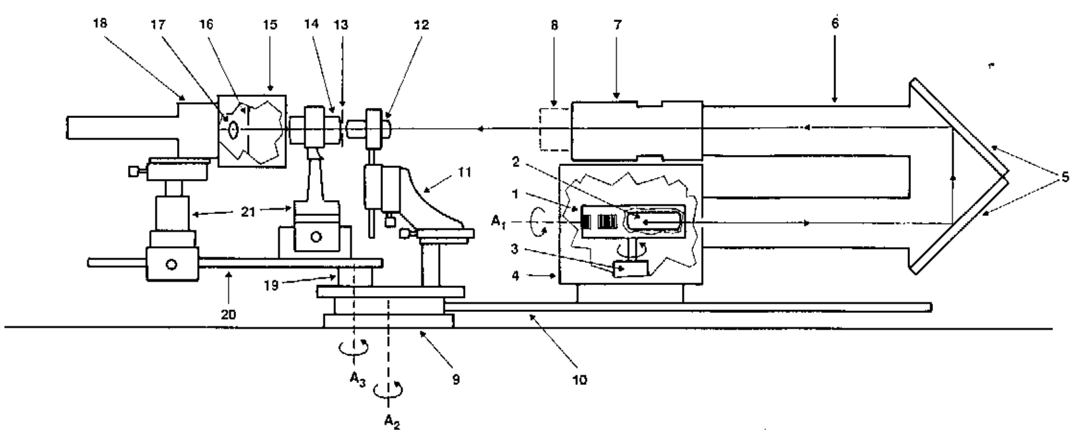

FIG. 2. Schematic of MTF apparatus. The target system comprises the target drum (1), illuminator (2), drum motor (3), drum housing (4), folding mirrors (5), light-tight housing (6), collimator lens for testing telescopes (7), and an additional relay lens for testing telemicroscopes (8). A_1 is the drum azimuth axis. The target system, on arm (10), pivots about axis A_2 of rotary stage (9). The optical mount (11) contains x-y-z micrometer stages and supports the device under test (12). The detector system consists of the diaphragm (13), relay lens (14), light-tight housing (15), slit (16), field lens (17), and PMT (18). The detector system is supported by transverse carriers (21) on an optical bench (20) that pivots about axis A_3 of rotary stage (19).

(monochromatic) or a broadband (white light) source.

A 48 in (121.92 cm) f/15 air-spaced achromatic astronomical objective lens collimates the targets via a folded optical path containing two 4.25 in (10.8 cm) diameter mirrors that are flat to 1/10 wave. The entire target system provides targets at any field angle by pivoting it about the rotation axis of a precision rotary stage.

The optical mount supports the test telescope in a centering chuck. The mount incorporates x-y-z micrometer stages for the precise alignment and positioning of the telescope. The telescope is positioned so that its objective lens coincides with the rotation axis of the rotary table.

The collimated output of the test telescope is stopped down by a diaphragm mounted to a 200-mm f/4 Nikon lens and located at the eye relief of Keplerian telescopes or about 15 mm from the oculars of Galilean telescopes. A 3-mm diaphragm, for example, effectively stops down to f/68 the 200-mm lens that relays the scanning images onto a 4-μm wide slit. Behind the slit is a field lens that images the aperture of the Nikon lens onto the photocathode of a photomultiplier tube (PMT), uniformly illuminating a fixed area of the photocathode. Interchangeable photomultipliers are used to optimize the spectral response of the system. Fig. 5 shows the calculated responses for the monochromatic and white light sources, using S20 and bialkali photocathodes, respectively. The curves are based on the measured color temperature of the source, and vendor-supplied values of the spectral transmittances of the filters and spectral sensitivities of the photocathodes.

The 200-mm relay lens and the slit/PMT are each mounted on optical bench carriers that are adjustable in the x-y-z axes. The carriers ride on a rigid optical bench which may be rotated about the axis of a second rotary stage centered at the diaphragm. The pivoting adjustments of the target and detector systems permit off-axis testing across the field of view of the telescopes. The processing electronics include a PMT output amplifier, an analog-to-digital converter, and an IBM PC XT microcomputer for data reduction and analysis.

TABLE 1. Target spatial frequencies in object space.

Telescope		Telemicroscope*
cpd	cycles/mm	cycles/mm
2.48	0.12	2.76
3.96	0.19	4.40
6.28	0.30	6.99
7.90	0.38	8.79
12.65	0.60	14.08
15.77	0.75	17.55
19.74	0.94	21.96
24.75	1.18	27.54
31.22	1.48	34.73
49.51	2.35	55.07
62.07	2.95	69.05
78.51	3.73	87.34
123.04	5.85	136.89
155.85	7.41	173.39

* Aerial image.

TELEMICROSCOPE AND FOCAL LENS TEST MODIFICATIONS

Many of the telescopes designed for low vision use have lens caps or are focusable for working distances that range from about 50 to 500 mm. A 50 mm f/1.8 Nikon lens attached to the collimator lens mount is the only modification needed to test these telemicroscopes. The lens produces aerial images of the square-wave targets, with spatial frequencies as shown in Table 1, to serve as near targets. A micrometer stage on the optical mount accurately positions the telemicroscopes at their working distances from these images.

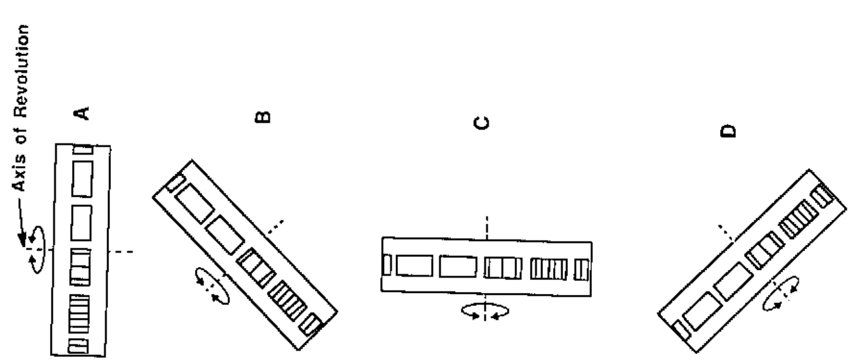

FIG. 3. Drum may be rotated to scan along four azimuths.

The MTF of focal lenses is measured simply by removing the relay lenses and permitting the lens under test to image the targets directly onto the slit.

OPTICAL SCHEMATIC

The optical schematic applicable to testing telescopes is shown in Fig. 6. The spatial frequency in object and image space may be expressed in cycles/millimeter (R) or cpd (ν). The width of one cycle (w) in the target subtends angle θ at the collimator lens with focal length f_c, where

$$\tan\theta = \frac{w}{f_c}$$

The equivalent number of cpd is

$$\nu = \frac{1}{\tan^{-1}\theta}$$

The spatial frequency in the image space of the telescope with angular magnification M is

$$\nu' = \frac{\nu}{M}$$

To convert back to cycles/millimeter at the slit (R′), the equation is

$$R' = \frac{1}{f_r \cdot \tan 1/\nu'}$$

where f_r is the focal length of the detector relay lens.

The spatial frequency in the aerial image (R_a)

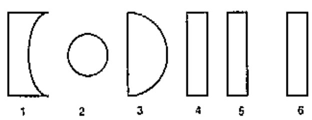

FIG. 4. Target illuminator contains the spherical mirror (1), 50 W 12 V quartz-halogen lamp (2), aspheric lens (3), Schott KG-1 heat filter (4), interference filter: 550 ± 8 nm for narrow passband or Schott FG-13 color compensating filter for white light (5), and diffuser (6).

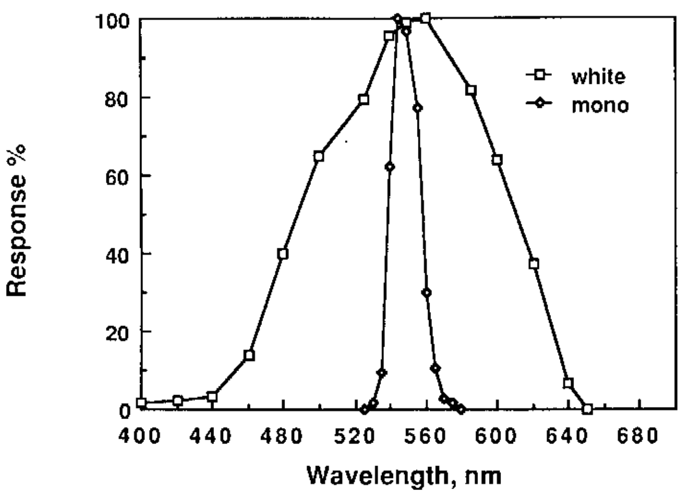

FIG. 5. Spectral response of MTF system with the S20 photocathode illuminated by the narrow passband source (mono), and with the bialkali photocathode and the white light source.

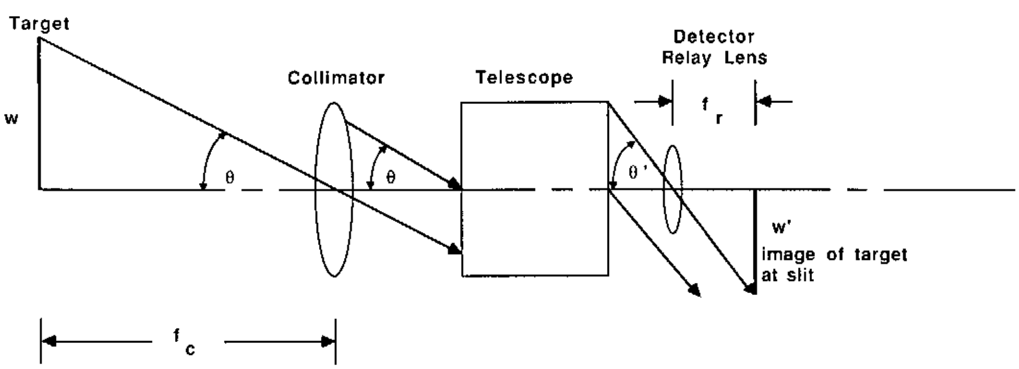

FIG. 6. Optical schematic to show relation between spatial frequencies in object and image space for testing telescopes.

that serves as the target for the telemicroscopes is given by

$$R_a = \frac{R \cdot f_c}{f_a}$$

where f_a is the focal length of the lens producing the aerial image.

TEST PROCEDURE

The device under test is visually aligned to center the output beam in the aperture of the diaphragm. The slit is positioned for best focus and centered on the image. Misalignment is especially severe with Pechan roof prism Keplerian telescopes. They commonly deviate the image along the direction of the roof edge, and away from the slit.[1] By mounting these devices with their roof edges horizontal the slit is centered simply by pivoting the detector system about its rotary stage.

The best focus MTF of telescopes is achieved by moving the slit/PMT system toward or away from the relay lens. Telemicroscopes are adjusted for best focus by positioning the aerial image at the optimum working distance.

The plane of best focus is determined at a specific spatial frequency, typically 5 cpd in image space. The actual and filtered data are shown on a computer-generated oscilloscope display along with the measured and diffraction-limited MTF values. The slit position, or working distance, is adjusted until the MTF is peaked, and the complete set of MTF values is collected. The diffraction-limited MTF is calculated according to equations from Smith.[17]

Off-axis telescope tests are conducted by pivoting the target system to the desired field position. The detector system is then pivoted until the images are centered on the slit. The optical mount and detector system are translated for off-axis telemicroscope tests.

METHOD OF OPERATION

We use the electro-optical Fourier method of scanning square-wave gratings across a slit. Square-wave targets are easier to produce than area or density type sine-wave patterns,[18] but must be filtered to remove all harmonics and noise. The spread function or light distribution in the image of the patterns that sweep across the slit is detected by a PMT which produces a voltage proportional to the illumination transmitted by the slit. The amplified analog output is converted to digital form and fed to a digital filter to obtain a sine wave for MTF analysis.

A digital filter was chosen over an electronic filter because of flexibility of design, freedom from temperature and/or time variations, and ease of implementation. A first-order recursive digital Butterworth bandpass filter, with a bandwidth of ±10% of the fundamental frequency at 3 dB attenuation, was developed using the bilinear Z-transform design method.[19]

A Metrabyte DASH-16 A/D board within the computer converts analog signals to digital form with direct memory access at rates of up to 50,000 conversions/s allowing for accurate representations (about 36 points per cycle) of even the finest target. Keeping the number of points per cycle constant for the different frequency targets by varying the A/D conversion rate allows the use of the same filter for the entire set of targets.

The filtered square wave is sinusoidal, as illustrated in Fig. 7. The modulation or contrast in the image is given by

$$\text{Modulation} = \frac{\text{Max} - \text{Min}}{\text{Max} + \text{Min}} = \frac{\text{Peak}}{\text{Mean}}$$

where the mean is the average of all values, and the peak is $\pi/4$ times the amplitude of the rectified wave. The MTF is the ratio of the modulation in the image to that in the object at each spatial frequency. However, the object is a black and white transparency with a modulation of one. Therefore, the MTF is equal to the modulation of the image.[17] The final MTF value is also corrected for attenuations by the bandpass filter and for the finite slit width, as described below.

A complete MTF curve and tabulated means, SD's, and departures from diffraction-limited performance, based on five revolutions of the drum, are produced in about 10 min.

SOURCES OF ERROR

The MTF measurements are subject to optical, mechanical, dimensional, electronic, and operational sources of error. All system lenses and mirrors must be diffraction limited. Resolution tests indicate that the collimator and relay lenses are diffraction limited at faster relative apertures than demanded in the apparatus. For example, the 3.25 in (8.26 cm) diameter f/15 collimator lens resolves group 7, element 2 of the U.S. Air Force resolution chart using a Wratten 74 filter with peak transmittance at 530 nm. This corresponds to 1.58 sec arc compared with a diffraction limit of 1.62 sec arc. In the apparatus this lens operates no faster than f/30. Similarly, the 200-mm Nikon relay is essentially diffraction limited. It too operates no faster than f/30, inasmuch as it is stopped down to match the pupil of the eye.

Other potential optical error sources that are controlled are stray light and fluctuations in the

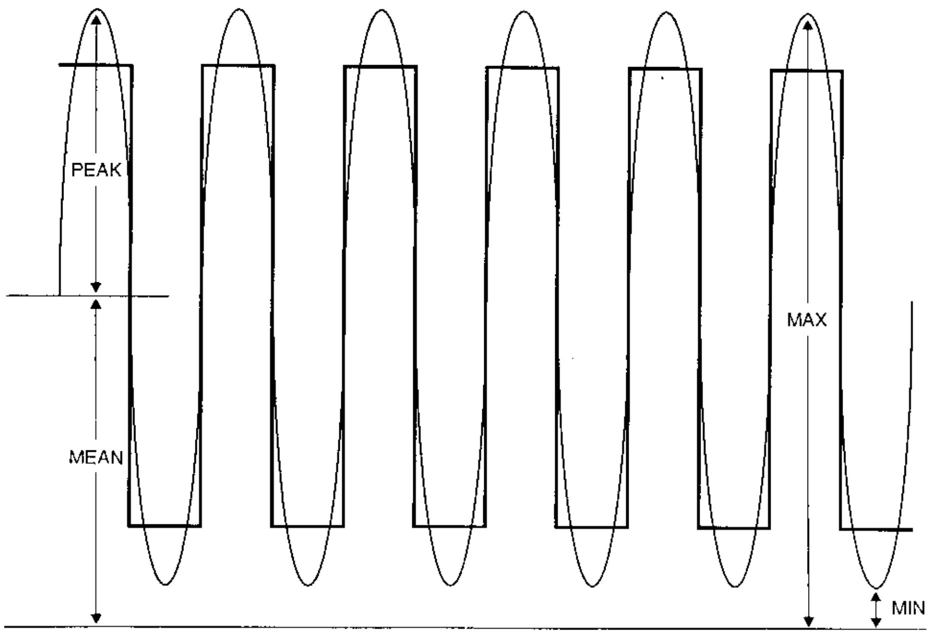

FIG. 7. The fundamental of a filtered square wave is a sine wave of the same frequency.

quartz-halogen lamp, which is operated with a regulated power supply and allowed to warm up until stabilized before running the MTF.

Mechanical and dimensional errors center on the photographic targets, drum, and slit. Analysis of the effect of unequal white and dark bars indicated that a difference of 3% would have an effect on the MTF of less than 1%. Multiple exposures of each spatial frequency were examined and measured with a micrometer microscope. The cleanest, sharpest, and highest contrast targets with minimum variations in width of white and dark bars were selected. The slit width was adjusted under the microscope. A correction of the MTF for the slit width is made according to the function[20]

$$C(R') = \frac{\pi R' a}{\sin(\pi R' a)}$$

where R′ is the spatial frequency at the slit and a is the slit width. This correction factor is incorporated into the data analysis program. Based on the highest spatial frequency encountered at the slit (44 cycles/mm) and a 4 μm slit width the correction factor never exceeds 5.3%.

Possible electronic sources of error are also minimized. Light levels at the PMT are sufficiently high to avoid threshold-level shot noise. Analog-to-digital conversion rates do not exceed limits of direct memory access on the computer.

Care by the operator in aligning the system and finding best focus is critical to accurate measurement. In addition to centering the system it is necessary to fine adjust the slit so that it is parallel to the square-wave targets. These adjustments are made interactively by peaking the MTF displayed on the oscilloscope.

Although the drum is driven by a synchronous motor, slight variations in drum speed can modulate input temporal frequencies slightly during data acquisition. This affects the digital filter response and lowers the MTF. An upward correction to the MTF, typically less than 0.5 dB or 5%, is made for the attenuation when the temporal frequency errors are within 10% of the expected frequency, otherwise the results for that target are rejected, as they are for unresolvable or spuriously resolved targets.

SYSTEM TESTS

A simple test of the validity of the apparatus, in the telescope test mode, can be made by measuring its own MTF. Without a telescope in place, but with the 200-mm relay lens stopped down to f/31.4 (6.4-mm pupil), the solid line in Fig. 8 would be the diffraction-limited MTF. The symbols represent measured values for the narrow and broadband spectral responses noted above. With the narrow spectral response the error in the measured contrast is less than 3% for spatial frequencies to 123 cpd, and about 1.6 MTF units (12.7%) at 156 cpd. The white light response is similar. The 2.1 MTF unit difference at 156 cpd corresponds to an error of 16.5% because the diffraction-limited MTF is only 12.8% at this spatial frequency. The symbols represent the means of five runs. As seen in Table 2 their SD's demonstrate the high reliability of the system.

Fig. 9 illustrates defocus MTF results for optical path differences for targets of the indicated spatial frequencies. A ¼ wave defocus is equal to

$$\frac{\lambda}{2\ n\ \sin^2 u} = \pm 1.08 \text{ mm}$$

where u is the slope of the marginal ray of an f/31.4 lens, $\lambda = 550$ nm, the peak wavelength of light, and n = 1, the index of refraction in image space.

DISCUSSION

An important factor in the satisfactory performance of the MTF apparatus is the use of square-wave targets, which are simpler to make and more precise than sine-wave targets. Their use followed from the decision to design a digital filter. Furthermore, the maximum spatial frequency required for testing the intended range of low power telescopes is less than 7.5 cycles/mm on the film. This makes sharp, high-contrast photographic reproductions feasible. These factors, and the control of the other noted error sources, are responsible for the high reliability and accuracy of the system.

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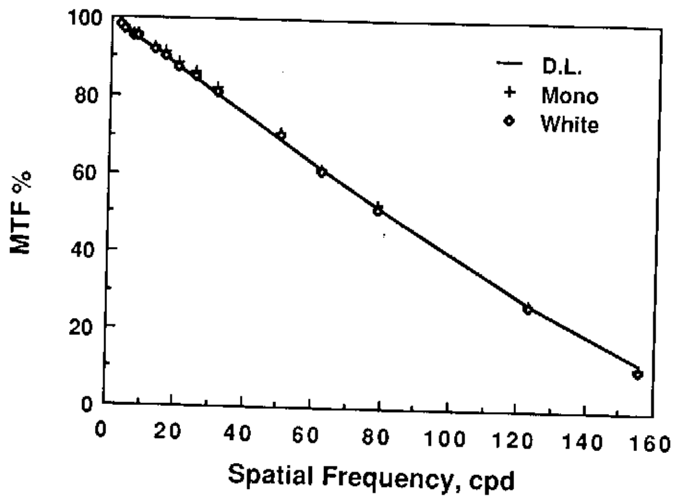

FIG. 8. The MTF of the apparatus in monochromatic and white light compared with the diffraction-limited MTF at f/31.4

TABLE 2. MTF test of system.

Spatial Frequency (cpd)	Diffraction Limited MTF (%)	Monochromatic			White Light		
		MTF (%)	SD	Error (%)	MTF (%)	SD	Error (%)
2.48	98.44	98.06	0.71	−0.39	98.33	0.24	−0.11
3.96	97.51	97.47	0.48	−0.04	97.05	0.43	−0.47
6.28	96.05	96.12	0.30	+0.07	95.26	0.67	−0.82
7.90	95.03	96.02	0.15	+1.04	95.26	0.28	+0.24
12.65	92.05	92.74	0.07	+0.75	91.84	0.24	−0.23
15.77	90.09	91.47	0.10	+1.53	90.35	0.25	+0.29
19.74	87.61	88.29	0.17	+0.78	87.44	0.25	−0.19
24.75	84.48	86.08	0.16	+1.89	84.87	0.24	+0.46
31.22	80.45	82.03	0.21	+1.96	81.18	0.16	+0.91
49.51	69.19	71.10	0.09	+2.76	70.31	0.23	+1.62
62.06	61.60	61.52	0.20	−0.13	60.98	0.36	−1.01
78.51	51.91	52.45	0.11	+1.04	51.16	0.27	−1.44
123.04	27.71	27.37	0.68	−1.23	26.59	0.23	−4.04
155.85	12.81	11.18	0.40	−12.72	10.70	0.17	−16.47

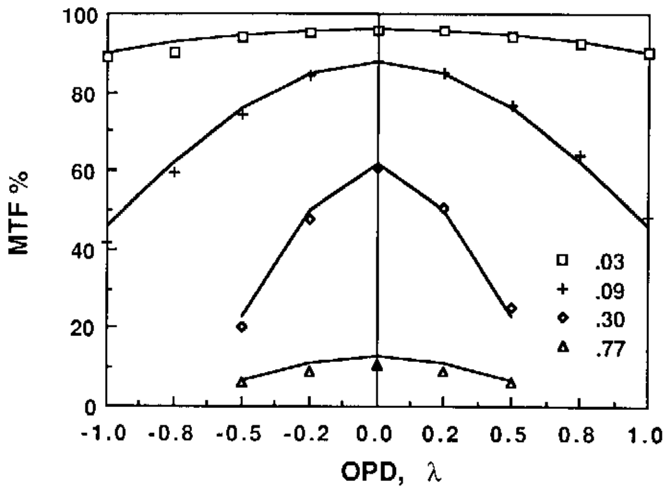

FIG. 9. The MTF of the apparatus in white light for indicated optical path differences (computed at 550 nm) for four spatial frequencies, compared with the diffraction-limited MTF at f/31.4.

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