PRECISION OPTICAL IMAGING

Section 1: Background

Research on random targets for modulation transfer function (MTF) evaluation began in 1986 at the Center for Education and Research in Optics and Lasers (CREOL) located at the University of Central Florida. *(1)* Under the direction of Dr. Glenn D. Boreman, research was conducted on the use of integrating spheres to produce highly uniform laser speckle. *(2)* Dr. Boreman demonstrated that the exit port of the integrating sphere could be used with a specially designed mask to produce laser speckle with a known power spectral density.

Al Ducharme began his Ph.D. research on MTF evaluation using random targets in 1990. His initial work built on Dr. Boreman's premise that an integrating sphere and mask could be designed that would generate a random target with known spatial frequency content. *(3)* The first projected random targets had a narrow-band power distribution with a center frequency inversely proportional to the distance between the image plane and integrating sphere. Since, the square root of the measured power divided by the input power, these narrow-band targets can be used to measure the MTF of a detector array. The MTF is measured over a range of frequencies by moving the detector array through a range of distances. Other masks were developed but the narrow-band target received the widest acceptance.

The one drawback of this method of target generation is that it is expensive. They system consisted of a visible laser diode with a constant current source, translation stage, integrating sphere, mask, and miscellaneous optical mounting hardware. Dr. Ducharme's Ph.D. dissertation concentrated on minimizing the complexity of the technique. *(4)* The first improvement was the reduction of the entire system to a single hologram of narrow-band laser speckle. *(5)* The resulting hologram can be used in a much simpler playback configuration consisting of only a few components. This hologram is now known as as the *Projected Random Test Pattern* (P-RTP) The second improvement came from the realization that a digital image could be created with a uniform or white-noise power spectrum. *(6)* The image can be imaged onto a detector array to measure the MTF over a wide range of frequencies using a single measurement (collection of measurements over a range of distances is not needed). The digital image is now known as the *Imaged Random Test Pattern (I-RTP)*. These patterns are part of the standard MTF target product line available from P.I.O.

Section 2: Modulation Transfer Function

The MTF of an optical system quantifies the ability of the system to resolve or transfer spatial frequencies. To understand this, imagine an imaging system such as the human eye observing waves of the ocean while the observer is riding in an aircraft, Assume that the altitude of the aircraft is increasing linearly and that the waves are of constant length (from peak-to-peak) and height, As the aircraft climbs the observer will begin to resolve the individual waves until finally the ocean appears flat. The altitude of the aircraft can be used to determine the spatial frequency in cycles/mm of waves on the retina of the eye. Therefore, the ability to resolve the waves plotted with respect to this frequency would in essence be the MTF of the human eye.

Although this is a simplified example it illustrates the following expression:

$$MTF(\xi) = \frac{M_{image}(\xi)}{M_{object}(\xi)}$$

where *M* is the modulation depth expressed as

$$M = \frac{E_{\max} - E_{\min}}{E_{\max} + E_{\min}}$$

and *E* is irradiance. Once the value of M_{image} is measured experimentally, the MTF value of the imaging system for the spatial frequency of the object can be calculated, The MTF is measured over a range or frequencies using a series of targets.

It is also acceptable to work in the frequency domain rather than the spatial domain. This is done using a fast Fourier transform (FFT) of the digitally recorded image. The absolute value of the result is then squared to yield the power spectral density (PSD) of the image, S_{image}. The MTF can then be evaluated using

$$MTF(\xi) = \sqrt{\frac{S_{image}(\xi)}{S_{object}(\xi)}}$$

Working in the frequency domain is an extremely useful technique since more complex targets can be used to measure MTF. Specifically, a random target with a known power spectrum can measure MTF for several frequencies simultaneously. This offers the following advantage over the other MTF measurement techniques:

A major problem encountered in measurement o MTF in sampled-image systems is that the image modulation depth depends on the position of the deterministic target with respect to the image sampling locations. A random target of known spatial-frequency content allows measurement of a shift invariant MTF because the information of the test target has random position with the respect to the sampling sites. The results is an extremely *repeatable* MTF measurement technique. (6)

Another item to remember when making MTF measurements is that all the systems components contribute to the final performance of your system. This cascading effect is expressed:

$$MTF_{system} = MTF_{framegrabber} \times MTF_{cabling} \times MTF_{detector} \times MTF_{lemses} \qquad (4)$$

Therefore, all of the planned system components should be used during the MTF testing.

1951

Section 3: Using the Imaged Random Test Pattern

The I-RTP is a square grayscale image with an uncorrelated two-dimensional random pattern. This pattern has a uniform bandlimited white-noise PSD. The bandwidth is equal to the number of pixels in a single dimension divided by two. *Since the spectrum of the I-RTP is white (i.e., equal power at all frequencies) the square root of the image PSD is equivalent to the MTF of the imaging system*. Yes, it is that simple. The MTF is measured for hundreds of spatial frequencies in two-dimensions using a single measurement.

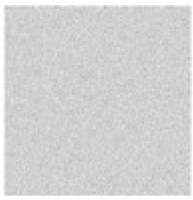

Figure 1. Sample Imaged Random Test Pattern.

Section 3.1: Measurement Configuration

To use the I-RTP you will need the target, imaging system and detector array, uniform lighting, and a method to digitally record and process a captured image. These items should be configured as shown in Fig. 2.

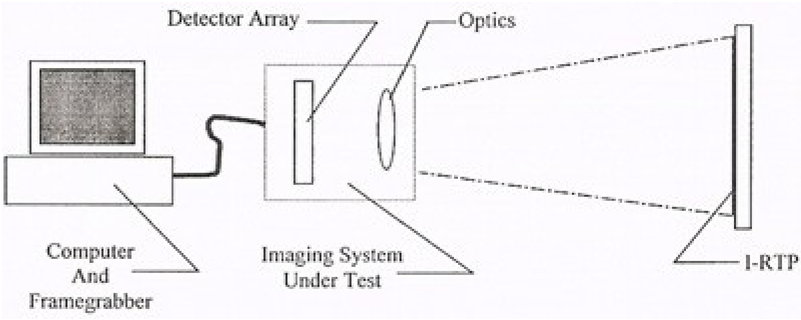

Figure 2. I-RTP measurement configuration.

The uniform light source is not shown in Fig. 2 but should be positioned so that image of the I-RTP has a uniform mean value. This is not critical but can add amomalous low frequency components to the measured PSD. Capturing an image of white paper and evaluating the digitally recorded pixel values can be useful when trying to obtain uniform illumination. There may be some applications where the system includes an illumination source. For this case, this source should be used when measuring the MTF of the system since the illumination will contribute to the overall system performance.

Section 3.2: Measurement Procedure>

The image of the target should be adjusted so that the field -of -view (FOV) of the imaging system is aligned with the dash-dot lines shown in Fig. 2. Ideally the target should be imaged 1:1 onto the detector array. This will enable the widest range of test spatial frequencies. An image (color or black-and-white) should be captured using a framegrabbing device. Preferably the framegrabber should be the one that is typically used in the application so that the MTF is representative of the entire system (i.e., the MTF described by Eq. 4). If the detector array is rectangular, which is usually the case, the edge of the target should be imaged onto the dimension of interest. The digital image of the target should be stored in a format that does not utilize compression (i.e., BMP rather than JPEG). In addition, if a color image with several color planes (e.g., Red 8-bit, Blue 8-bit, and Green 8-bit) is captured then only a single plane should be used in processing.

3.3 Data Processing

In order to process the image you will need a standard FFT algorithm available in most programming languages. The first step in the program must be to convert the image to a double precision 2D array. Then the mean value of the array is subtracted from the image. If you are familiar with Fourier theory, this last step will eliminate the dominant frequency component at 0 cycles/mm. A program should be written that performs the following diagram on the $N_x \times N_y$ image of the target.

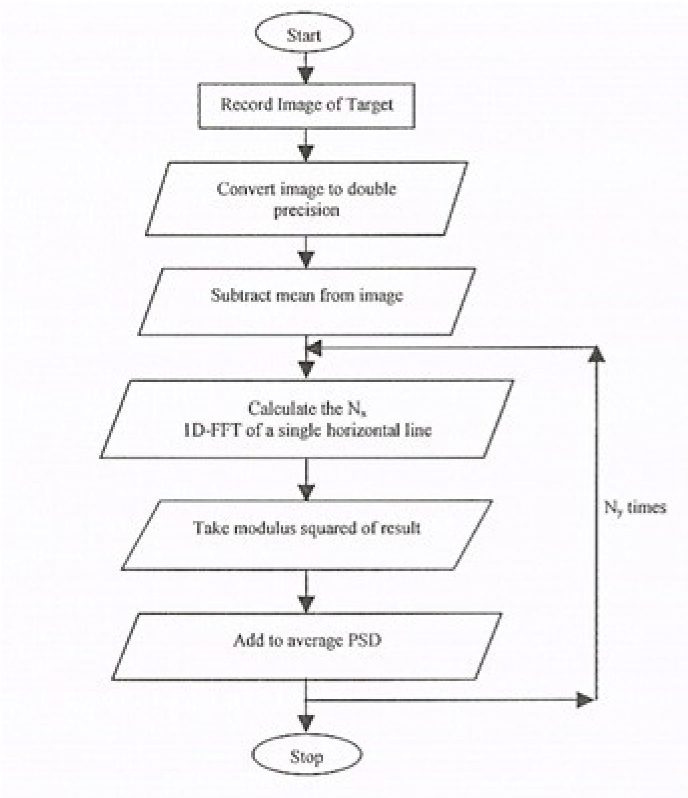

Figure 3. Flow diagram of algorithm to determine PSP estimate.

In words, the processing algorithm forms a PSD estimate of the image in one dimensions. The estimate is the result of the average of N_y spectums. The resulting PSD array will have N_x-1. Since the PSD is inherently positive frequencies , 0 to N_x/2-1, and negative frequencies, N_x/2 to N_x-1. Since the PSD is inherently symmetric we can discard the negative frequencies. The resulting array will have N_x/2 vaues. The final processing step is to scale teh PSD array so that it represents the MTF of the system under test. This is done by evaluationg Eq. 3 now expressed

$$MTF(\xi) = \sqrt{\frac{S_{image}(\xi)}{1}}$$

since the input power is 1 for all frequencies.

The final three steps are used to scale the data into MTF units. First, the MTF array must be normalized to the lowest frequency component in the array with the exclusion of the value in array index value 0. This is acceptable since the lowest frequencies will be passed through the system with little or no attenuation. The MTF curve should be smooth near 0 cycles/mm and the normalization should make the low frequencies equal to 1.0. Second, you must take the square root of the PSD yielding the MTF y-axis array. Finally, the frequency- or x-axis array must be created with units of cycles/mm. This is done using the following expression:

$$\xi(I) = \frac{I}{d_x N_x}$$

where d_x is the width of a single detector in the x dimension, ξ(I) is the x-axis array, and I is the array index value from 0 to $N_x/2-1$.

The resulting y-axis MTF array is plotted against the x-axis frequency array. This plot represents the MTF of your system in the *x* dimension. The same procedure can be repeated for the *y* dimension to evaluate the MTF of your system in the orthgonal axis.

Section 3.4: Specification of 1-RTP

Parameter	Value
Light wavelenght range	400nm-to-800nm
Lowest Test Frequency	1/Width of detector array (cycles/mm)
Highest Frequency	600/Width of detector arrat (cycles/mm)
Physical Form	Matte paper on foam core
Size	6" x 6"

Section 4: Using the Projected Random Test Pattern

The P-PTP is a hologram of a random target produced by exposing holographic film with narrowband laser speckle. Illuminating the hologram with a coherent light source such as a visible laser pointer replays the P-PTP. When .illuminated at the recording angle, a real image of the narrow-band laser speckle is projected onto a detector array *with no intervening optics*. This has the advantage of eliminating the MTF of the lens system, which may be desirable in some applications. The difference between the I-RTP and the P-RTP is that the P-RTP tests one spatial frequency for each captured image in only the horizontal dimension. Translating the detector array with respect to the hologram tests additional frequencies.

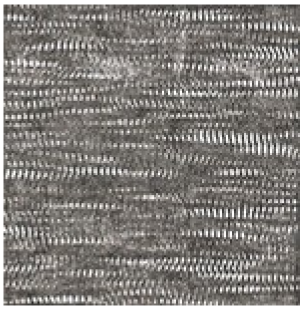

Figure 4. Sample Projected Random Test Pattern. The domination spatial frequency can be seen in the horizontal dimension of the image.

Section 4.1: Measurement Configuration

To use the P-RTP you will need the target, a laser source, a method to translate the detector system, a negative lens, and a method to digitally record and process a captured image. These items should be configured as shown in Fig.5.

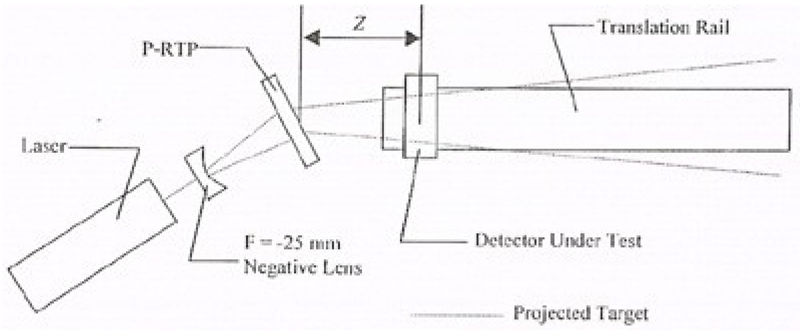

Figure 5. P-RTP measurement configuration.

The negative lens is used to expand the collimated beam from the laser source. The angle between the illumination and target is approximately 40 degrees and must be adjusted during set-up. The angle between the target and optical axis of the projected target is equal to the illumination angle. The orientation and incident sides are marked on the hologram.

Section 4.2: Measurement Procedure

The image of the target should be adjusted so that the field-of-view (FOV) of the imaging system is aligned with the dotted lines shown in Fig.5. An image (color or black-and-white) should be captured using a frame grabbing device. Preferably the frame grabber should be the one that is typically used in the application so that the MTF is representative of the entire system (i.e., the MTF described by Eq. 4). If the detector array is rectangular, which is usually the case, the edge of the target should be imaged onto the dimension of interest. The digital image of the target should be stored in a format that does not utilize compression (i.e., BMP rather than JPEG). In addition, if the color image with several color planes (e.g., Red 8-bit, Blue 8-bit, and Green 8-bit) then only a single plane should be used in the processing.

The distance, *Z*, between the hologram and detector determines the spatial frequency being tested. The relationship is expressed by

$$\xi \approx \frac{1}{Z}$$

Therefore, high frequencies are tested close to the hologram and low frequencies are tested far from the hologram. This is analogous to the effect observed when moving an overhead projector away from a screen. The image gets larger as the projector is moved farther away from the screen. The exact distance does not need to be measured since the tested frequency will be evident in the processed PSD..

Section 4.3: Data Processing

The PSD of the P-RTP target is narrow-band meaning that it has a known spectral power that is concentrated over a small range of frequencies. The theoretical P-RTP PSD is shown in Fig. 6.

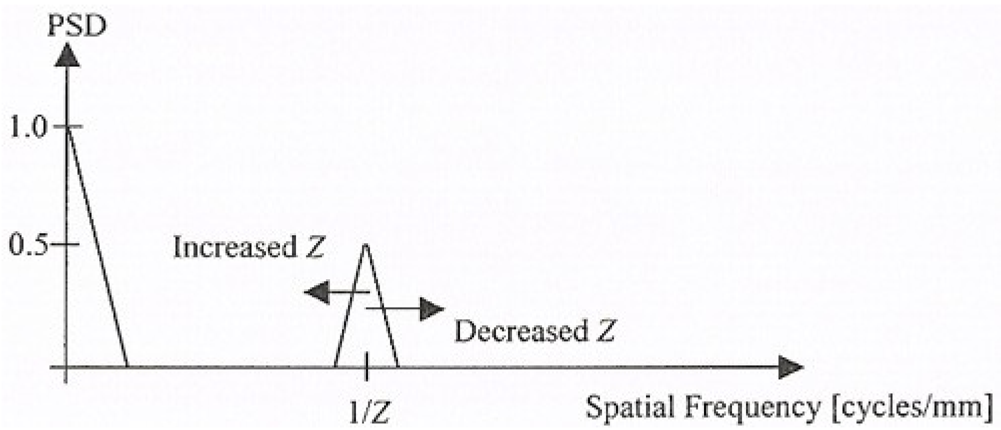

Figure 6. Theoretical PSD of P-RTP.

This figure illustrates the movement of the narrowband peak as *Z* is varied. The beauty of this technique is that the power of the triangular peak is always 1/2 of the central peak. As a result. Eq. 3 can be expressed as

$$MTF\left(\frac{1}{Z}\right) = \sqrt{\frac{S_{image}\left(\frac{1}{Z}\right)}{\frac{1}{2}}}$$

To begin making an MTF measurement you must position the detector array until an image of a single speckle covers half of the image. After an image has been digitally captured and stored, the detector array is moved towards the hologram until approximately 2 speckles can be seen in the image. This same distance increment is used until the target no longer illuminates the entire detector array. Each stored image is then processed using the method described in section 3.3 up to the point before you take the square root of the PSD estimate. Instead, the square root of the height of the narrowband peak divided by 1/2 is evaluated. The result is the modulation transfer at the *index value* of the PSD array. The corresponding frequency will be evaluated when all MTF values are measured. The MTF value is stored in an array of sizes $N_x/2$ at the same index value where the peak value was positioned. Once all of the images have been processed the resulting MTF array should be plotted against the x-axis or frequency array described in section 3.3. The MTF of the detector array in the orthogonal axis can be measured by repeating this process with the detector array rotated 90 degrees.

Section 4.4: Specification of P-RTP

Parameter	Value
Light wavelenght range	600nm-to-700nm
Lowest Test Frequency	1/Width of detector array (cycles/mm)
Highest Frequency	>600/Width of detector arrat (cycles/mm) *
Physical Form	35 mm projection slide
Size	2" x 2"

* Depends on how close the detector array can be positioned from the hologram.

Section 5: References

1. G. D. Boreman and E. Dereniak, "Method for measuring transfer function of changed-coupled devices using laser speckle." *Opt. Eng.*, **24**, pp. 148-150 (1986)

2. G. D. Boreman, Y. Sun, and A. James, "Generation of laser speckle with an integrati *Eng.*, **29**. pp. 339-342 (1990)

3. M. Sensiper, G. D. Boreman, A. D. Ducharme, and D. R. Snyder, "MTF testing of detector arrays using narrowband laser speckle," *Opt. Eng*., **32**(2), pp. 395-400 (1993).

4. A. D. Ducharme, "Signal-processing and flux-transfer issues for laser speckle." *Ph.D Dessertation*, Univ. Central Florida (1994).

5. A. D. Ducharme and G. D. Boreman, "Holographic elements for the modulation transfer function testing of detector arrays," *Opt. Eng*. **34**(8), pp. 2455-2458, (1995).

6. A. Daniels, G. D. Boreman, A. D. Ducharme, "Random transparency targets for modulation transfer function measurement in the visible and infrared regions," *Opt. Eng*., **34**(3), pp. 860-868 (1995).

Precision Optical Imaging

www.precisionopticalimaging.com

Sales & Accounting Office
62 Honeoye Falls 5 Pts Road
Rush, N.Y. 14543
Phone: 585-533-9133
Fax: 585-533-9193

Manufacturing Office
7466 West Henrietta Rd.
Rush, N.Y. 14543
Phone: 585-533-4040
Fax: 585-533-9193

President: allen.bolognesi@precisionopticalimaging.com
Sales:sales@precisionopticalimaging.com
CAD Manager: cad@precisionopticalimaging.com