Random targets for modulation transfer function testing

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ABSTRACT

Tests for modulation transfer function (MTF), particularly for staring systems, are affected by the position of the test target with respect to the rows and columns of the detector array. To alleviate the position-dependent nature of the measurement, we have developed a target that uses random patterns of known spatial-frequency content. In this way a phase-averaged MTF is measured, which is indicative of field performance on natural scenes.

1. INTRODUCTION

A major problem encountered in MTF measurements is that the measured modulation depth in the image is dependent on the position of the test target with respect to the rows and columns of the focal-plane array (FPA).[1–3] A test target has been developed which is random in nature. This target measures the phase-averaged MTF of the imager under test, from zero spatial frequency to the Nyquist frequency, rather than measuring a phase-specific MTF such as is obtained with targets with a deterministic structure (i.e., point source, line, or bar target).

Recently another method called the scanning-knife-edge method[4] has been developed to solve the phase problem of array sensors. This method consists of scanning a narrow slit over a single pixel on the detector array. The random-target method however surpasses the scanning method because it requires no mechanical scanning and because it tests more than one pixel at a time.

The random-target method creates random test patterns similar to those created using the laser-speckle method,[5] but on a broadband basis, without the use of laser radiation. This allows use of blackbody radiation for the source. This method tests both the FPA and the optics together, whereas the speckle MTF tests only the FPA.

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Proof-of-principle experiments were performed by printing several different random patterns in transparencies, and imaging onto a visible charge-coupled device (CCD) FPA.

2. SYSTEM DESIGN

A computer algorithm to generate random targets with the desired spectral properties was written by creating a vector of N random numbers, where N defines the resolution of the target image. This vector is inserted into a loop to generate an array of N×N random numbers, resulting in an uncorrelated two-dimensional random pattern with the uniform bandlimited white-noise distribution shown in Fig. 1. Figure 2 is a schematic of the setup used to measure MTF using these random patterns.

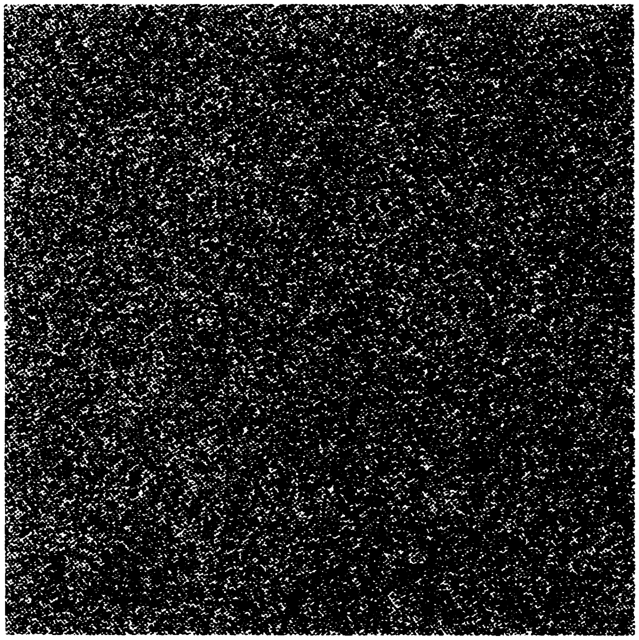

Figure 1. Bandlimited white-noise random image.

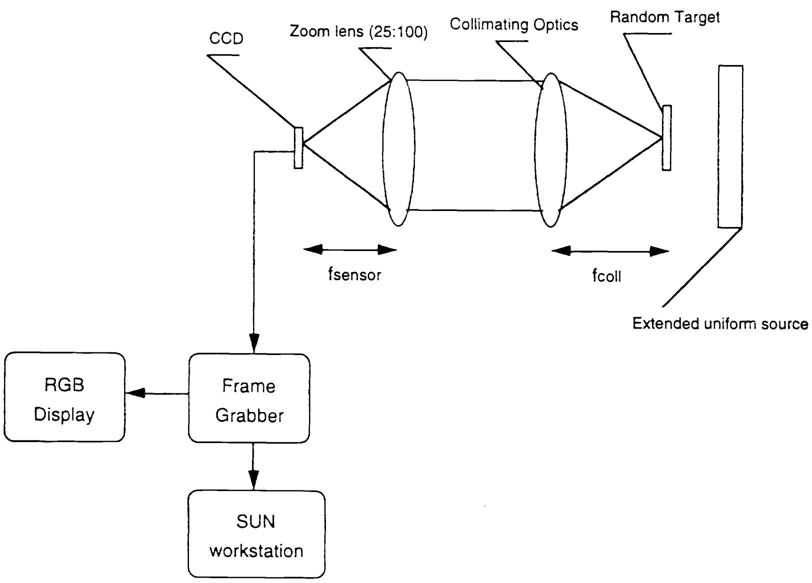

Figure 2. MTF experimental setup.

The random pattern is printed into a transparency and placed in front of the uniform lighted background, creating a two-dimensional radiance pattern. This pattern introduces optical spatial noise of known spatial power spectrum PSD_{in} into the system. A typical profile of the white-noise spectrum of the input image is shown in Fig. 3.

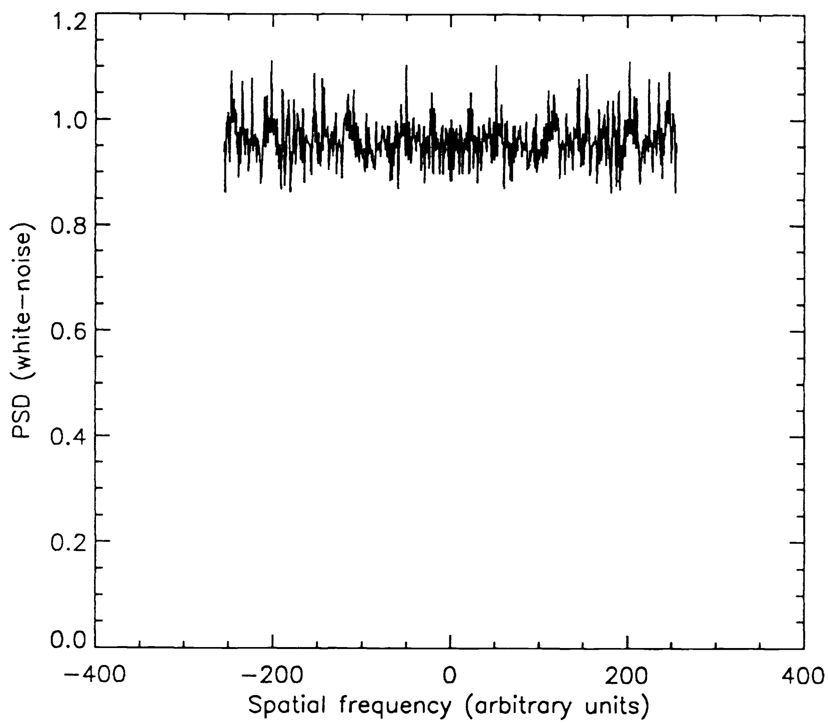

Figure 3. White-noise spectral distribution.

The output power spectral density PSD_{out} can be estimated by imaging the target through the optical system onto a CCD FPA. The output image data are then captured by the frame grabber and processed.

PSD_{in} and PSD_{out} are functions of the spatial frequency (ξ) in one direction of the random pattern, and are related in the following manner:

$$PSD_{out}(\xi) = |H(\xi)|^2 \cdot PSD_{in}(\xi) \ , \tag{1}$$

where $H(\xi)$ is the system transfer function or MTF of the system.

The resulting MTF using the random target of Fig. 1 is called the "continuous" MTF because it provides a continuous curve for all spatial frequencies of interest. In addition, another method was developed called the "discrete" MTF, which allows us to measure the MTF at a number of discrete spatial frequencies and hence acquire the signal-to-noise ratio (SNR) as a function of spatial frequency, which is an important characterization, especially for signal-dependent noises such as shot noises.

This method was implemented by generating a filter representing a discrete narrowband PSD at specific spatial frequencies of constant amplitude (shown in Fig. 4). This filter is then multiplied by the white-noise spectrum of Fig. 3 in the frequency domain, and Fourier transformed to obtain the desired discrete narrowband random image shown in Fig. 5. Note how the selected spatial frequencies in the filter appear in the image (i.e., a certain correlation between pixels exists), in comparison with the continuous case (see Fig. 1) where no correlation exists between pixels whatsoever.

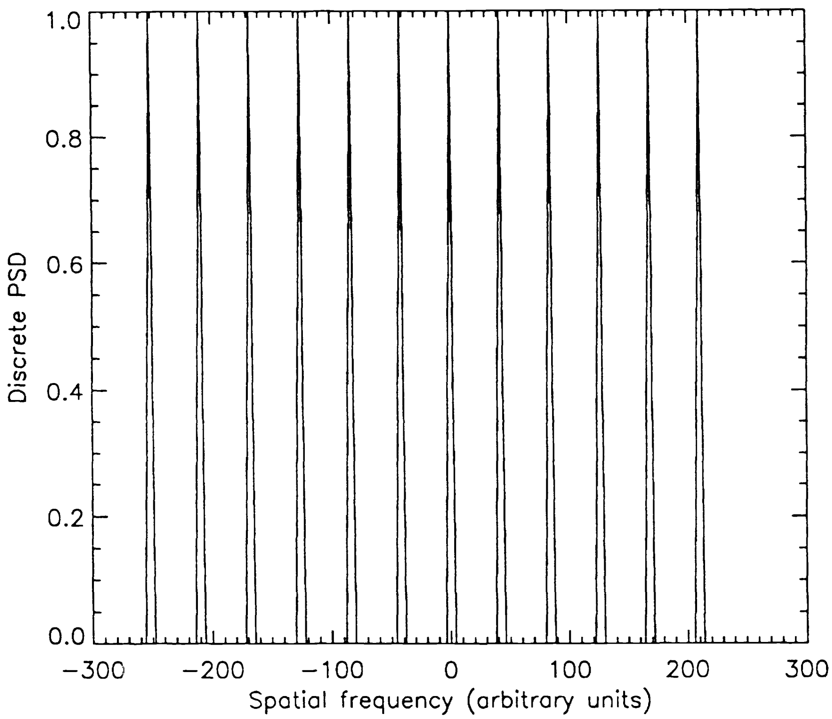

Figure 4. Discrete input power spectral density (PSD_{in}).

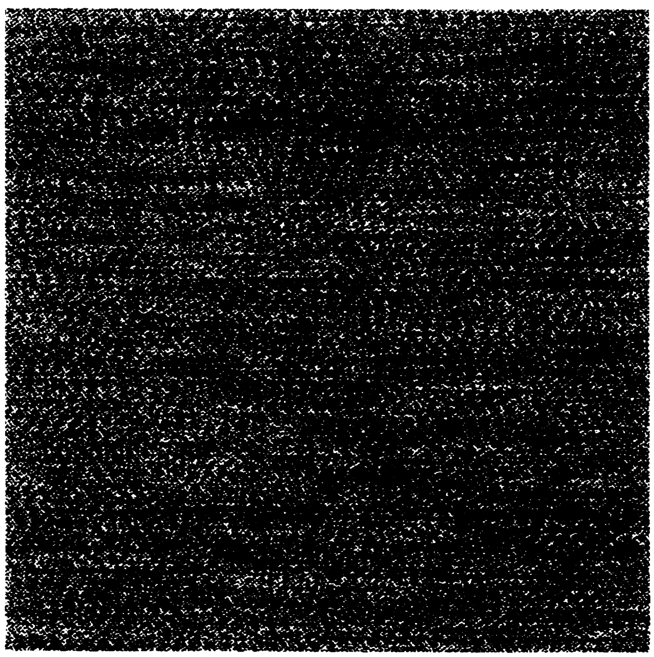

Figure 5. Discrete narrowband random image.

This algorithm avoids undesired attenuations at the input of the system which would be present if the PSD of a laser speckle[5] (i.e., autocorrelation function) were used instead. Therefore in this case the attenuation factor of the PSD at the output of the system solely results from the system MTF. This constancy in the PSD makes the MTF measurable to higher spatial frequencies than would be possible if the PSD_{in} were bounded by an autocorrelation.

The spatial frequency ranges were calculated in to span the frequency response of the sensors used in the demonstration. Thus, we are able to compare our results with the MTF measurements using standard methods. The MTF data were smoothed by a moving-window technique in the frequency domain.

3. ANALYSIS AND TECHNIQUE LIMITATIONS

The goal here is to optimize the pixel size of the random target to avoid aliasing. This is acomplished by calculating the overall resolution of the system.

The pixel size of the random target imaged through the optics and falling upon the FPA is calculated by

$$l = \frac{L \cdot M}{N} \quad [\mu m] \, , \tag{2}$$

where L is the length of the random target, N is the desired resolution of the random target, and M is the magnification of the system which is given by

$$M = \frac{f_{sensor}}{f_{coll}} \, , \tag{3}$$

where f_{sensor} is the focal length of the zoom lens $(25 - 100\ mm)$ and f_{coll} is the focal length of the collimating optics.

The maximum spatial frequency that can be created at the FPA is given by

$$\xi_{max} = \frac{1}{2 \cdot l} \quad [pixels/mm] \, , \tag{4}$$

where l is calculated in Eq. (2).

To avoid aliasing, ξ_{max} must be less than or equal to the spatial Nyquist frequency of the FPA under test, which for detectors with a center-to-center spacing d is given by

$$\xi_{Ny} = \frac{1}{2 \cdot d} \quad [pixels/mm] \, . \tag{5}$$

The ultimate frequency resolution of the measurement is determined by the discrete Fourier transform (DFT) relationship between number of points in one domain and the number of points in the other domain (equal number of points in both domains). For the case of the "continuous" MTF measurement, the minimum spacing of the frequency components that can be generated is

$$\Delta\xi = \frac{1}{2 \cdot L} \quad [pixels/mm] \, . \tag{6}$$

In the discrete case, 10 triangles would be sufficient to determine the MTF curve and at the same time define an appropriate guardband, so that the noise as a function of spatial frequency can be measured.

In test situations where the focal length of the sensor is small compared to the focal length of the collimator, a high spatial resolution on the transparency is required, because the random nature of the target is preserved if a sufficient number of independent fringe regions are imaged onto the FPA. The resolution of the printing device must be sufficient to meet this requirement for any given relay magnification going from target to FPA.

4. EXPERIMENTAL MEASUREMENTS AND RESULTS

4.1. Continuous MTF

Measurements were performed using the setup in Fig. 2. Both the random MTF method and standard (line-spread function) method were used to facilitate a comparison. The physical parameters used in the system were

$d = 23.4\ \mu m$
$f_{sensor} = 35\ mm$
$f_{coll} = 250\ mm$
$L^* = 100\ mm$ with a resolution of $N^* = 512$ pixels

where L^* and N^* are the length and resolution of the printed picture. However, only $L = 61\ mm$ was imaged into the FPA, decreasing the resolution to $N = 312$ pixels. The system was then evaluated using Eqs. (2) through (5)

From Eq. (2): $l = 27.4\ \mu m$
(3): $M = \frac{1}{7.14}$
(4): $\xi_{max} = 18.25$ cycles/mm
(5): $\xi_{Ny} = 21.36$ cycles/mm.

The resolution of the system was measured using a slit target of width $w = 0.1 mm$. In this case the slit was moved relative to the sampling sensor grid until maximum and minimum signals were obtained at the sensor output. In this case the spatial frequency cutoff (the first zero of the sinc function) for the slit image is approximately $\xi_{slit} = 18$ cycles/mm.

The results from the slit method and the random method are compared in Fig. 6. The random MTF is given by the solid curve, and the maximum and minimum standard MTF by the dashed and dotted curves respectively. Note that the random MTF curve lies between the maximum and minimum line-response MTF curves. The random-target method measures a phase-averaged MTF.

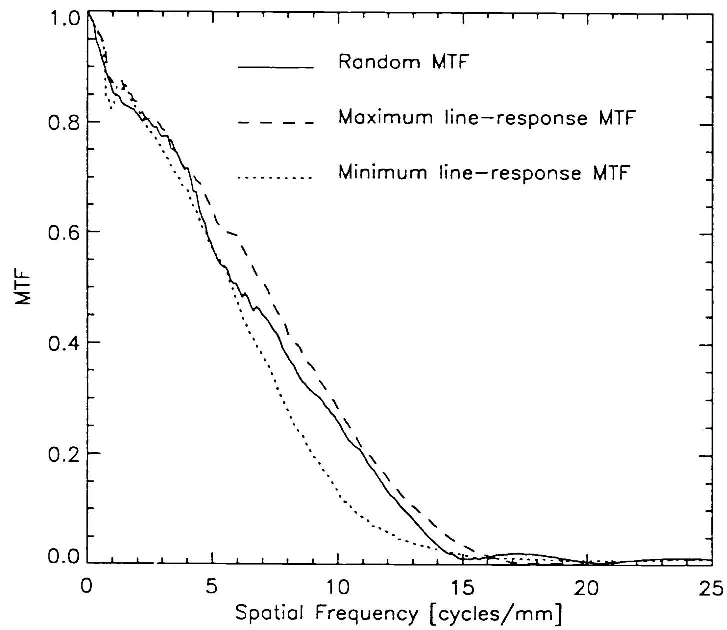

Figure 6. Random MTF (solid line); maximum-line response (dashed line); minimum-line response (dotted line).

Comparison between four different continuous curves are shown in Fig. 7. Table 1 shows the parameters used for the measurement of these curves.

MTF Curves	Table 1. Parameters for random MTF curves						
	f_{coll}	f_{sensor}	L	N	M	l	ξ_{max}
1	300	35.62	71.5	332	8.42	25.5	19.59
2	300	35	73	339	8.57	25	19.94
3	300	30	88	409	10	21.5	23.27
4	300	27.5	102	474	10.9	19.7	25.36

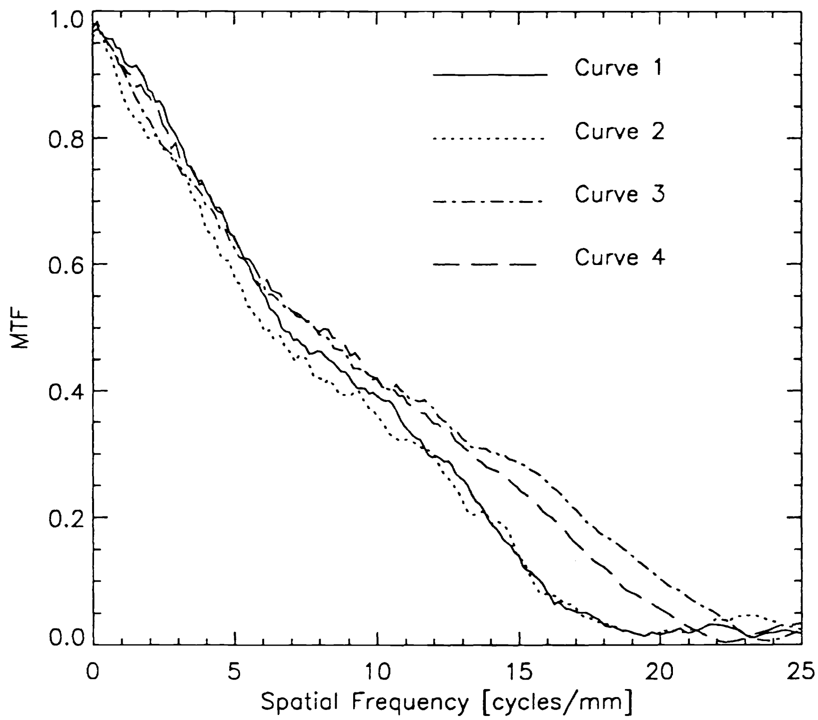

Figure 7. Different random MTF curves
The parameters used are shown in table 1.

Curves 3 and 4, which go beyond the Nyquist frequency of the detector, are higher because frequencies above Nyquist are folded to lower frequencies. Once the frequency of the input target passes ξ_{Ny}, aliasing effects occur, distorting the measured MTF curves. Thus, the input PSD must have a maximum spatial frequency less than Nyquist.

4.2. Discrete MTF

An additional experiment was performed analyzing the discrete target of Fig. 5, using the methodology of section 4.1. In this case the parameters used were:

$f_{coll} = 300\ mm$; $f_{sensor} = 30\ mm$; $L = 86\ mm$; $N = 314\ pixels$; $M = \frac{1}{10}$; $l = 27.4\ \mu m$ and $\xi_{max} = 18.25\ cycles/mm$

The resulting discrete MTF is shown in Fig. 8. The filtering effect of the MTF can be clearly seen in the decrease in height of the triangle peaks comparing Figs. 4 and 8. The results of both methods are superimposed in Fig. 9; note how the continuous curve fits the height of each of the discrete points.

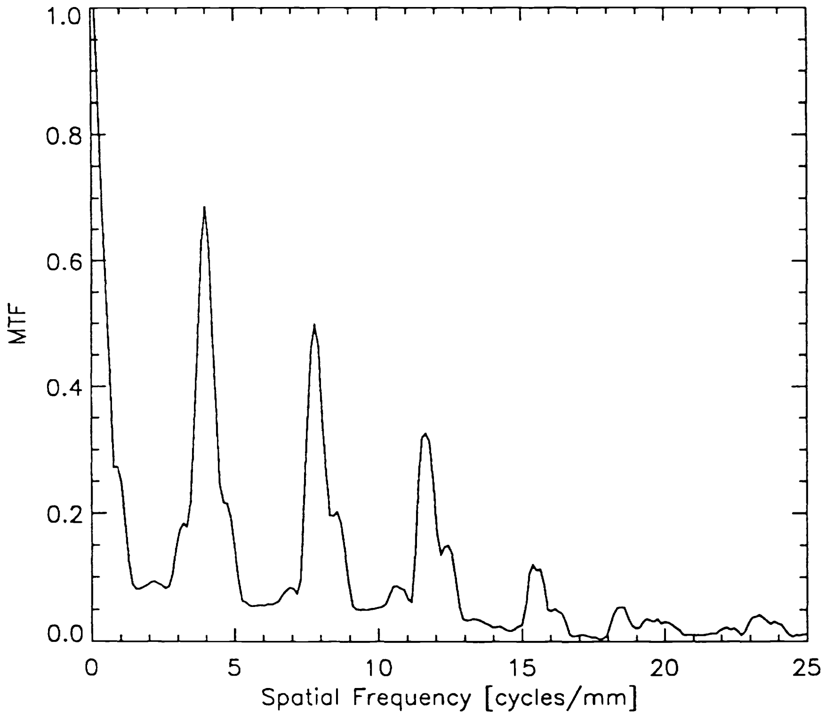

Figure 8. Discrete MTF.

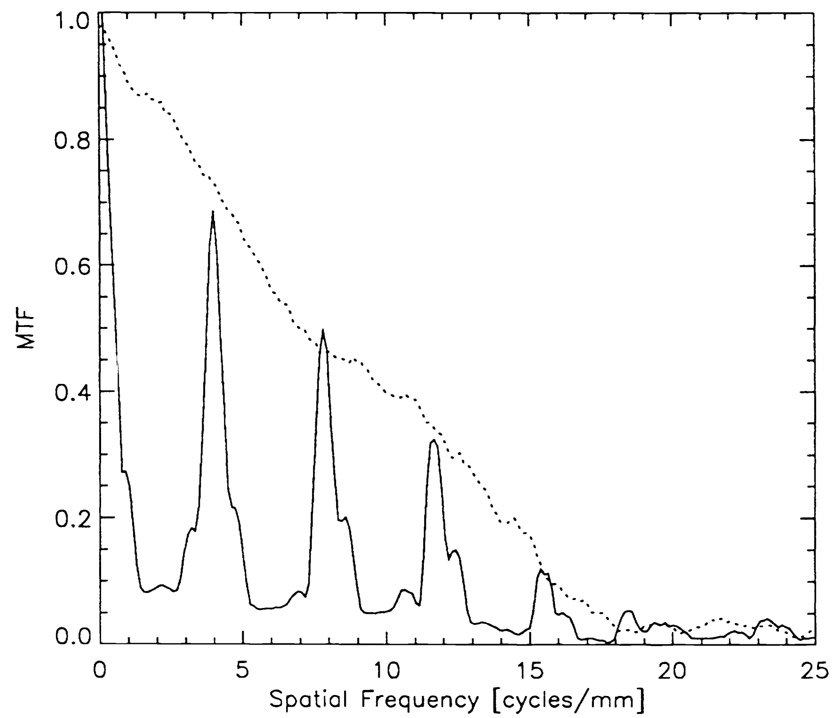

Figure 9. MTF curves: discrete (solid line); continuous (dotted line).

5. CONCLUSIONS

A random-target method of MTF testing for both staring and scanning systems has been developed. This target, which is random in nature, yields a way to direct measure the phase-averaged MTF, which is more representative of the response of an imaging system to natural scenes. This new target also allows us to measure MTF at a number of discrete spatial frequencies, which will permit the calculation of the noise as a function of spatial frequency along with the MTF. MTF measurements were also performed by the standard method of line response for comparison. The methods give good agreement. The random-target measures the phase-averaged MTF lying between the maximum and minimum line-response MTF.

6. AKCNOWLEDGMENT

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7. REFERENCES

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