Use of Spatial Noise Targets in Image Quality Assessment

Glenn Boreman and Arnold Daniels
Center for Research in Electro-Optics and Lasers
Department of Electrical Engineering
University of Central Florida
Orlando, Florida 32816

Introduction

Image quality is typically specified by modulation transfer function (MTF), which can be measured using one of a number of common test targets: line source, point source, bar targets, sine waves. However, the use of these deterministic targets with spatially-pixelated systems requires careful alignment of the targets with respect to the sampling sites. For example, as seen in Figure 1, a line-response test will produce various test results depending on the exact alignment of the line-source image with respect to the sampling sites of the pixels. This variation is termed sample-scene phase dependence.[1] The alignment is especially critical at spatial frequencies approaching the spatial Nyquist frequency $\xi_{\mathrm{Nyquist}} = 1/(2\Delta x)$, where Δx is the spatial separation between samples. Our approach uses targets of a random nature, with a known power spectral density (PSD) as a function of spatial frequency as inputs to the system. The MTF is calculated from the output PSD data as:

$$\mathrm{MTF}(\xi) = \{\mathrm{PSD}_{\mathrm{output}}(\xi)/\mathrm{PSD}_{\mathrm{input}}(\xi)\}^{1/2} \quad . \tag{1}$$

This approach is commonly used to characterize time-domain electrical networks, and its application to the MTF testing of pixelated imaging systems provides an averaging of sample-scene phase, which eases alignment tolerances and facilitates MTF measurements at spatial freqencies near or beyond ξ_{Nyquist}.

Figure 1. MTF measurement of a pixelated system using a line-source method exhibits variation caused by sample-scene phase.

Target Generation

Two basic methods are used for target generation, for two separate applications. For characterization of MTF of detector arrays alone, the optimum method for target projection does not require intermediate projection optics. Laser-speckle techniques are appropriate in this instance, because the mechanism of target projection is diffraction. For characterization of the MTF of a complete imaging system (detector array and imaging optics together), the imaging optics should be tested with the detector array. For these applications, random transparency targets are used in conjunction with a high-quality collimator.

The optical train of Figure 2 generates laser speckle patterns of known PSD. The output of the integrating sphere is a spatially uniform irradiance, with spatially random phase. The aperture following the integrating sphere determines the PSD of the speckle pattern at the detector array, which is proportional to the autocorrelation of the aperture transmission function.[2] Typically, a double-slit aperture is used, which produces a double-sideband PSD as seen in Figure 3. The sideband center frequency is

$$\xi_{center} = L/\lambda z , \qquad (2)$$

where L is the center-to-center separation of the slits and z is the aperture-to-focal-plane distance. Changing z tunes the spatial frequency of the resulting narowband speckle pattern. A typical speckle pattern is seen in Figure 4. The strength of the sideband frequency component does not change as ξ_{center} is tuned, and MTF can be calculated from the relative strength of this component at the output of the system, according to Eq. (1).

Figure 2. Optical train for laser-speckle test target generation.

Figure 3. Double-slit aperture (3.a) used for speckle generation, and the PSD (3.b) of the resulting target.

Figure 4. Speckle pattern target resulting from the use of the double-slit aperture.

The optical train of Figure 5 projects a random transparency target into a complete imager system. The collimator MTF must either be known at the frequencies of interest or high enough not to affect the results. The transparency is fabricated by either xerographic exposure of a plastic film (for use in the visible and the 3- to 5-μm infrared band) or electron-beam lithography involving a metal film on a transparent substrate for use in the 8- to 12-μm infrared band. The transparency pattern is computer generated by first using a random number generator to create an array (n × m) of uncorrelated random numbers. This array is Fourier transformed, spatially filtered to produce the desired autocorrelation and PSD characteristics, and inverse transformed. The shape of the resulting target PSD is more general than the PSD resulting from the laser-speckle process discussed above, because it is no longer constrained to be an autocorrelation function. In Figure 6 the target transparency pattern is shown for a flat low-pass PSD that is constant out to a cutoff frequency. The cutoff frequency of the pattern is usually set to be less than or equal to $\xi_{Nyquist}$ of the detector array, taking the two-element relay magnification into account from the projection system seen in Figure 5. For transparency-based test systems, the multiple-discrete PSD seen in Figure 7, along with the resulting target pattern, can also be created. In the multiple-discrete PSD, each of the sideband peaks can be of equal height. This can be used for test scenarios where sampling at several discrete frequencies is desired.

Figure 5. Typical optical train for projection of transparency targets.

Figure 6. Target transparency pattern for a flat low-pass PSD.

Figure 7. PSD (7.a) and target transparency pattern (7.b) for multiple-discrete frequencies.

One advantage of the transparency-based test is that MTF over a range of frequencies (continuous or discrete) can be measured simultaneously. The laser-speckle method is generally used in a one-frequency-at-a-time test procedure, because the laser-speckle PSD is an autocorrelation, which yields a decreasing function of spatial frequency for bandpass or multiple-discrete PSDs. The PSD does not necessarily fall off with frequency in the transparency-based systems, which yields better signal-to-noise ratio at the higher test frequencies.

Test Results

Figure 8 shows the output PSD from a double-slit laser-speckle test on a detector array. The solid line corresponds to a sideband center frequency less than $\xi_{Nyquist}$ of the detector array, while the dashed line corresponds to a frequency higher than $\xi_{Nyquist}$, which has been aliased to a lower frequency. Given that the center frequency can be calculated with Eq. (2), no ambiguity is introduced by the aliasing and the MTF can be measured at frequencies both below and above $\xi_{Nyquist}$.

Figure 8. Output PSDs from double-slit laser-speckle test. Solid line corresponds to a spatial frequency below Nyquist, dashed line corresponds to a spatial frequency above Nyquist.

Figure 9 shows an MTF curve measured by a flat low-pass target, as in Figure 6, along with a maximum and minimum MTF curve measured by a line-response technique.
The random-transparency target measures the sample-scene-phase-averaged MTF, which lies approximately halfway between the maximum and minimum MTFs.

Figure 9. Comparison of MTF measured with flat low-pass random transparency to maximum and minimum MTFs measured using line-response technique.

Figure 10 shows the MTF curve measured with the discrete narrowband transparency of Figure 7, along with an MTF curve measured with a low-pass transparency, and the noise amplitude spectrum shown for reference. Good agreement exisits between the two MTF measurements, with the added benefit that the multiple-discrete PSD target allows simultaneous measurement of the noise amplitude spectrum in the guard bands between the discrete signal frequencies. This might facilitate the use of spatial-frequency-dependent signal-to-noise ratio as a conveniently measurable figure of merit for imaging systems.

Figure 10. Comparison of MTF measured with multiple-discrete-frequency transparency to MTF measured with a flat low-pass transparency. Also shown is the noise amplitude spectrum.

Conclusions

The advantages of spatial-noise targets for MTF testing of pixelated systems are that they inherently measure a sample-scene phase-averaged MTF, resulting in relaxed alignment tolerances and more consistent measurements. This class of targets can test both detector arrays alone and complete systems, over a range of spatial frequencies extending past the spatial Nyquist frequency. These techniques are applicable over a wide range of wavelengths.

References

1. S. K. Park, R. Schowengerdt, and M. Kaczynski, "Modulation-transfer function analysis for sampled image systems," *Applied Optics* 23, 2572-2582 (1984).
2. J. Goodman, "Statistical properties of laser speckle patterns," in *Laser Speckle and Related Phenomena*, J. C. Dainty, Ed., pp. 35-40, Springer-Verlag, Berlin (1975).