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Method for Measuring Modulation Transfer Function of CCD's Using Laser Speckle

G. Boreman* and E. L. Dereniak

Optical Sciences Center, University of Arizona
Tucson, Arizona 85721

Abstract

A new method has been developed to measure the modulation transfer function (MTF) of an array out to the Nyquist frequency without high-quality optical or mechanical components, without precision alignment, and with only one moving part. Test results for an infrared staring array of PtSi Schottky barrier construction show that this technique is a viable MTF measurement approach in the 3 to 5 μm spectral regions.

Introduction

The measurement method depends on the determination of a system transfer function by means of a series of random inputs. The input $S_{in}(\xi,\eta)$ and output $S_{out}(\xi,\eta)$ power spectra of a two-dimensional system are related in the following manner:

$$S_{out}(\xi,\eta) = |H(\xi,\eta)|^2 S_{in}(\xi,\eta), \qquad (1)$$

where $H(\xi,\eta)$ is the system transfer function. In the present application, the system transfer function is the MTF of the device. Laser speckle provides an input of optical spatial noise of known spatial power spectrum into the system. The output power spectrum is computed directly from the array data.

Speckle Properties

Speckle is an interference phenomenon observed when coherent radiation is scattered from a rough surface. A point-to-point variation in optical intensity is observed at all planes beyond the scatterer. This variation of optical intensity has a spatial power spectrum described by the autocorrelation of the intensity distribution in the scattering aperture.[1] Hence, for a scattering geometry as shown in Figure 1 with uniform illumination on the aperture, the input power spectrum is a triangle function for spatial frequencies greater than zero as shown in Figure 2. For nonuniform illumination of the aperture, the power spectrum is no longer a perfect triangle function, but can be described by the autocorrelation function of the aperture. Thus, a known input power spectrum is provided that allows the MTF of the CCD to be inferred from the array data.

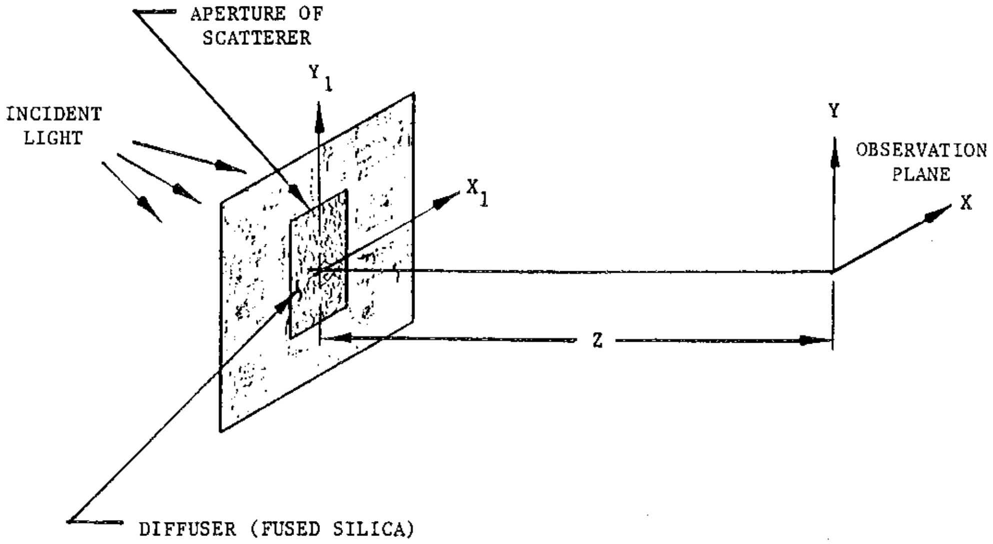

Figure 1. Free space propagation geometry for speckle formation.

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* Now at the Department of Electrical Engineering, University of Central Florida, Orlando, Florida 32816

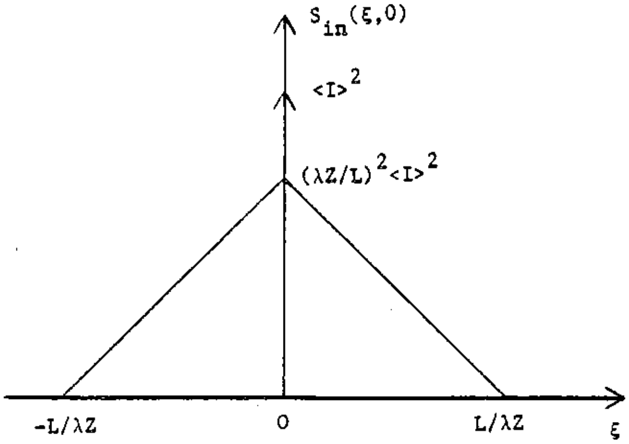

Figure 2. ξ-profile of input power spectrum of speckle.

Instrument Design

The instrument, shown in Figure 3, was designed to measure the MTF of an infrared CCD at 3.39 μm under the following conditions. The upper frequency limit of the input power spectrum was chosen to be the Nyquist frequency for the array so as to avoid problems of aliasing in the output array data. To express the power spectrum of the speckle as an autocorrelation of the aperture intensity function, the structure on the diffuser surface had to be unresolvable at the detector plane. It is thus implied that

$$\Delta < \frac{\lambda Z}{D}, \tag{2}$$

where Δ is the surface correlation distance on the scatterer, λ is the laser wavelength, Z is the distance from the CCD array to the scatterer, and D is the CCD linear dimension. This condition was satisfied by the sandblasted surface of the fused silica diffuser shown in Figure 4. Another configuration of the apparatus was used to image the scattering aperture onto the array plane so that the autocorrelation of the aperture intensity function, and hence the input power spectrum, could be computed. Use of the data acquisition system shown in Figure 5 allowed speckle data to be collected. A typical frame with the background subtracted is shown in Figure 6.

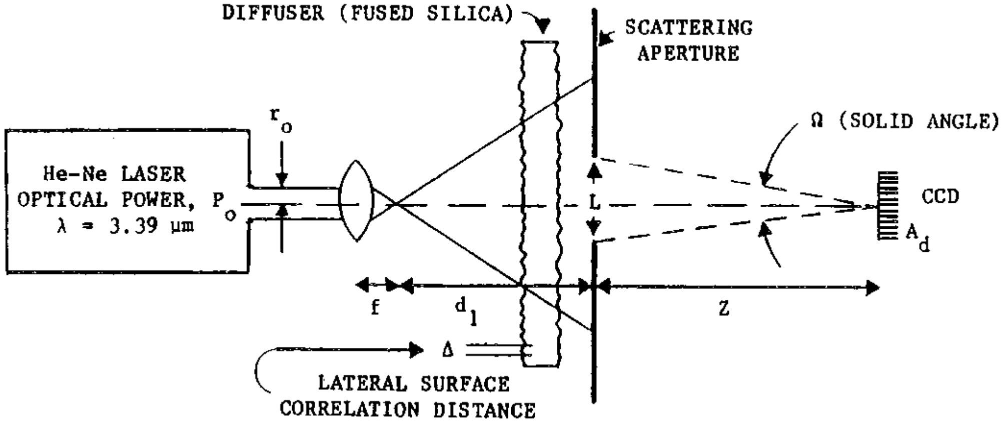

Figure 3. Speckle MTF measuring instrument. P_0 = 5 mW, r_0 = 1 mm, f = 12.7 mm, d_1 = 200 mm, L_x = 4.25 mm, L_y = 8.5 mm, Z = 300 mm, Δ < 0.25 mm, A_d = 14.75 mm^2.

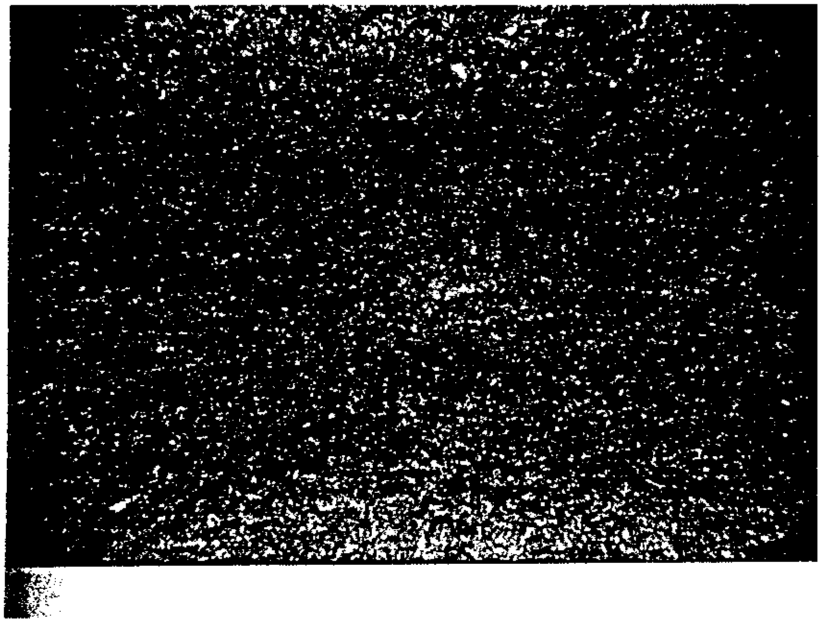

Figure 4. Photograph of diffuser surface.

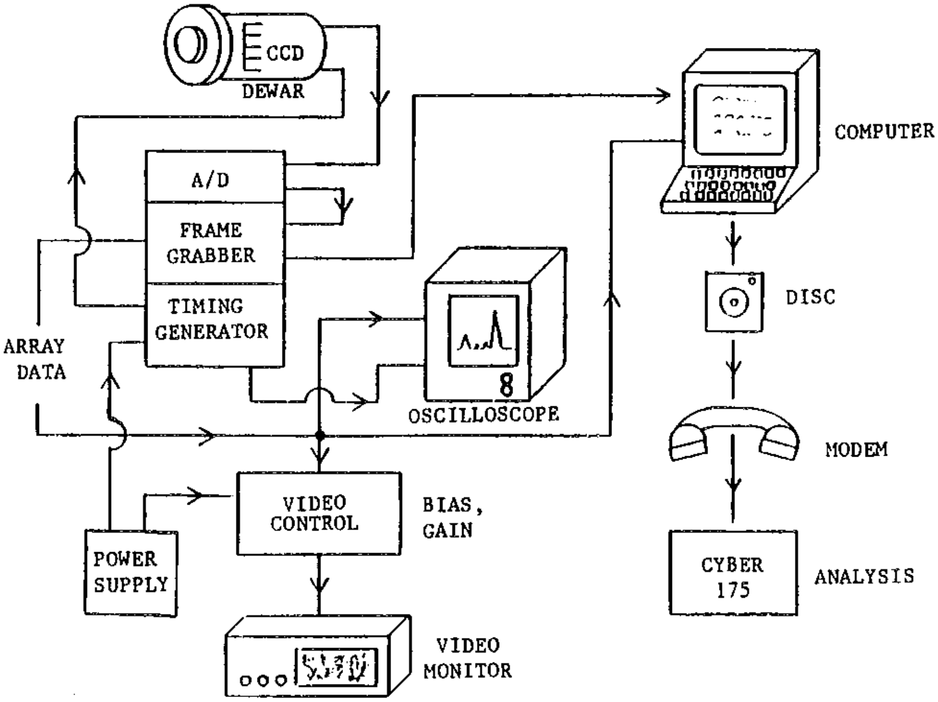

Figure 5. Data acquisition system.

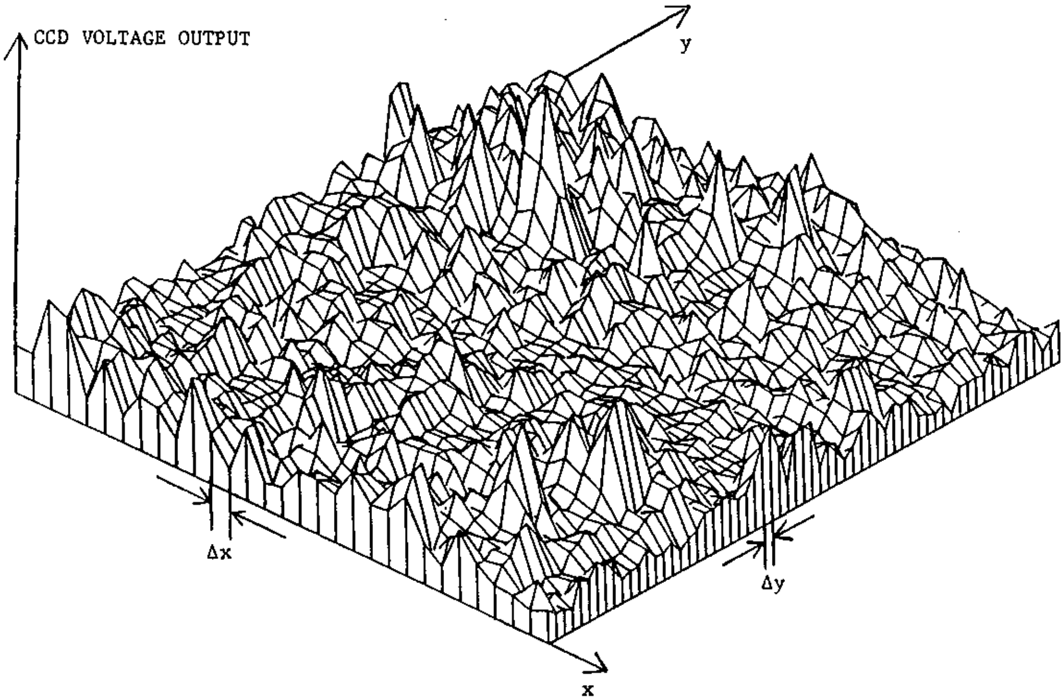

Figure 6. Typical frame of speckle data.

Data Processing

The output power spectrum, necessary for the calculation of MTF, is determined in the following manner. A fast Fourier transform (FFT) was performed on each row of speckle data, and the squared magnitude was taken to produce a power spectrum. Each of the row spectra was normalized individually by dividing the strength of each frequency component by the sum of all components up to the Nyquist frequency in that particular spectrum. This procedure weighted each row of data equally, rather than by the amount of power in that row. Similar procedures were applied to data in the y direction to obtain η spectra. These normalized spectra were averaged over the rows and columns of each frame and over 10 frames of speckle data. The ensemble averaging over different frames of speckle data is necessary to reduce the variance in the estimate of the output power spectrum.[2] The diffuser was moved during the acquisition of successive frames of speckle data.

The input power spectrum is also necessary for the calculation of the MTF, and was calculated from the normalized autocorrelation of the aperture intensity function. The procedure used consisted of an FFT operation and squaring, then an inverse FFT to obtain the autocorrelation of the real-valued aperture intensity function.

Results

The MTF results in both the ξ and η directions for the infrared CCD array tested are seen in Figure 7. There is an eventual rise in the calculated MTF values as the Nyquist frequency is approached, since the input power spectrum goes to zero at that frequency, while the output spectrum still has a finite baseline value due to noise. The lower MTF values in the ξ direction are a result of the architecture for the particular array under test. There was a higher charge transfer speed in the x direction than in the y direction, so the MTF was lower in the direction of faster charge transfer primarily due to the effects of charge transfer inefficiency. These results were closely corroborated by interferometric and impulse response tests on the same device.

Conclusions

The advantages of this method of MTF measurement are that it does not require high precision optical nor mechanical components nor is precise alignment needed. There is only one moving part in the system (the diffuser), and its motion is not critical. From each frame of data, an estimate of MTF for the device as a whole is available at all frequencies less than the Nyquist in both the ξ and η directions. These factors make the system an ideal candidate for the automated testing of CCD's in a production environment.

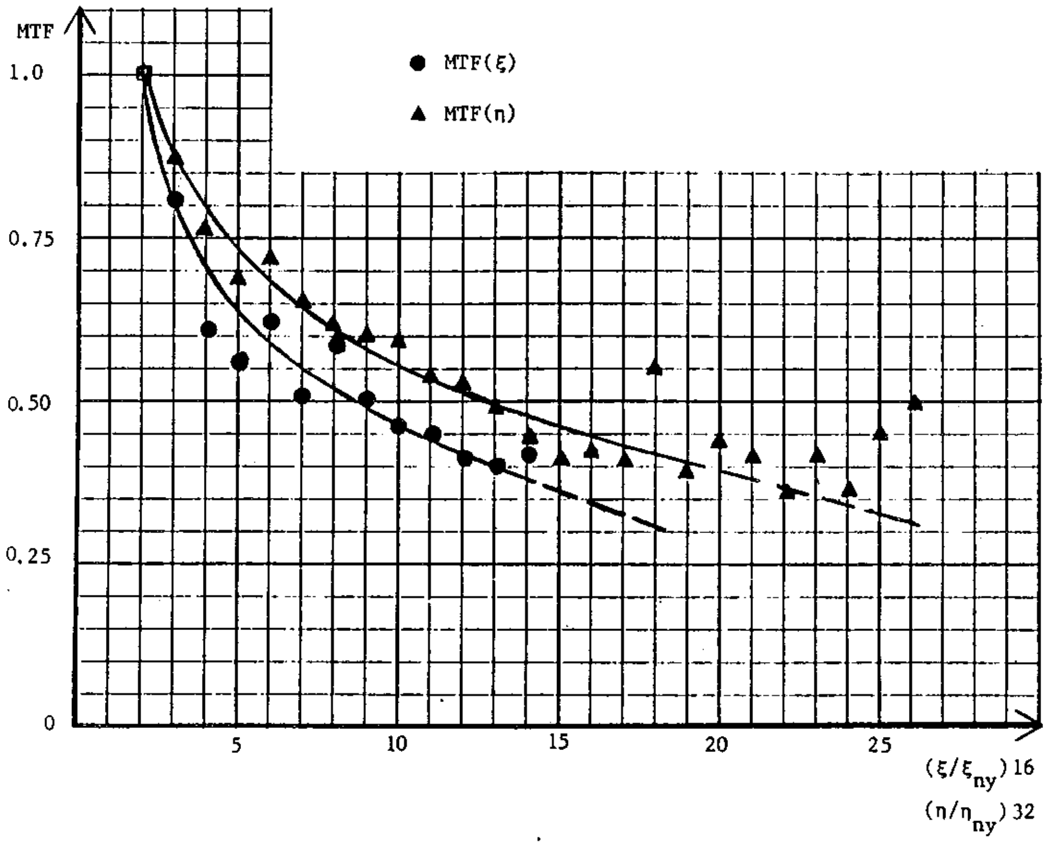

Figure 7. MTF results from the speckle method.

References

1. Goodman, J., "Statistical Properties of Laser Speckle Patterns," in Laser Speckle and Related Phenomena, J. C. Dainty, ed., Springer-Verlag 1975.
2. Bendat, J. S., and Piersol, A. G., Random Data: Analysis and Measurement Procedures, Wiley 1971.