A Modulation Transfer Function Measurement Technique for Small Pixel Imagers

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Motivation

Characterize the imaging behavior of CCD imagers with 5µm pixels for the **HRTS/OSL** mission (A high resolution, imaging, UV spectrograph).

Objectives:

- Characterise large focal plane array- **2000x20,000 pixels** total.
- Measure **spatial resolution** via pixel response function.
- Measure small **resolution differences** across the array.

Measurements should be directly applicable to the **spectral range** of **120-175nm** on back-side illuminated or Lumogen coated imagers.

Except for the spectral region, our requirements are shared by many other applications using **small pixel, large format imagers.**

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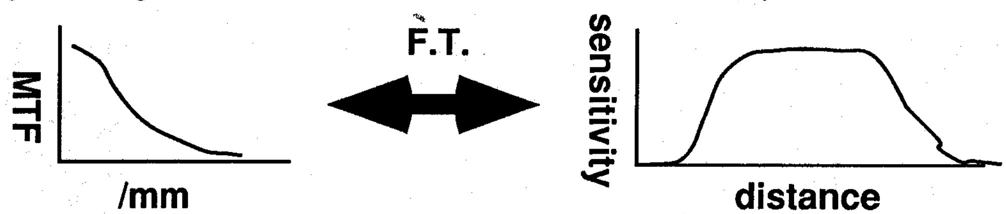
Strategy

To characterize the spatial resolution of the imager:

- **Characterise the MTF at several visible and UV wavelengths to 200/mm.**
  - 514nm: Lumogen Emission Peak.
  - 300nm: Silicon absorption length minimum.
  - 600nm: Characterize charge diffusion effects.

- **Fourier Transform MTF to obtain pixel response function**
  (ignore slight error due to CTI and electronics effects)



- **Compare results with other techniques: point response, models, empirical spectrograph performance, etc.**

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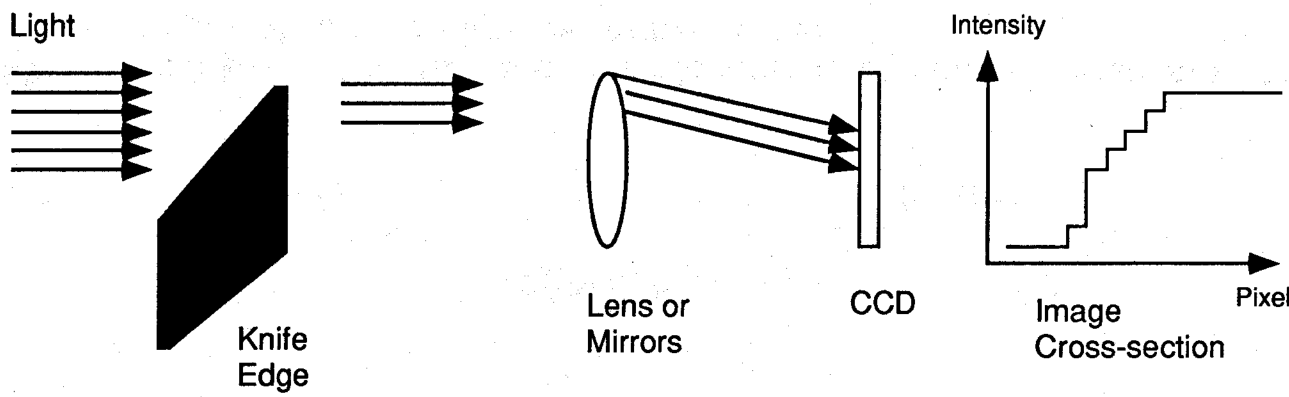
Common MTF Measurement Techniques

For example, see the following talk by Lomheim.

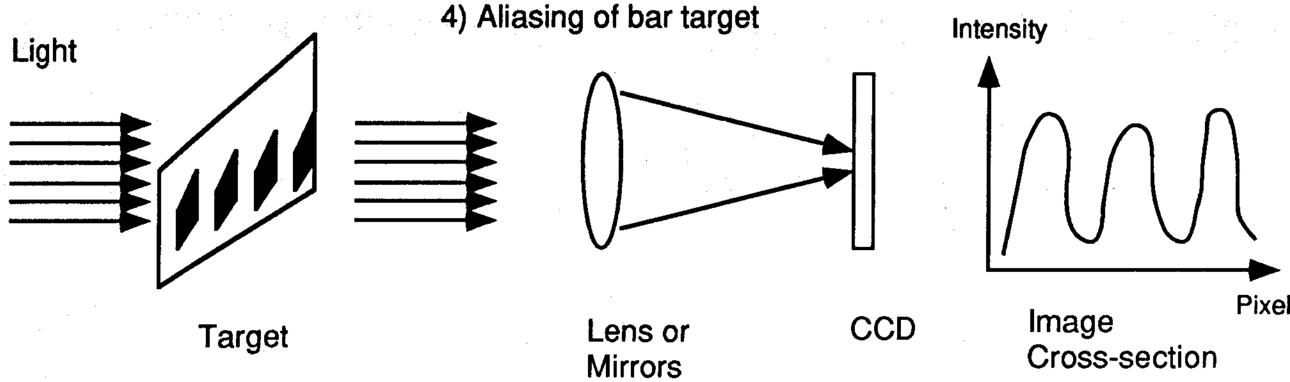
Knife Edge: Image a knife edge to obtain imager step response.
Point response is similar.

Limitations: 1) Finite extent of image
2) Effect of lens is hard to accurately compensate
3) Aliasing cannot be avoided



Pattern Target: Image a sinusoidal density or bar pattern.

Limitations: 1) Finite Extent of image
2) Effect of lens is hard to accurately compensate
3) Fidelity of sine target
4) Aliasing of bar target



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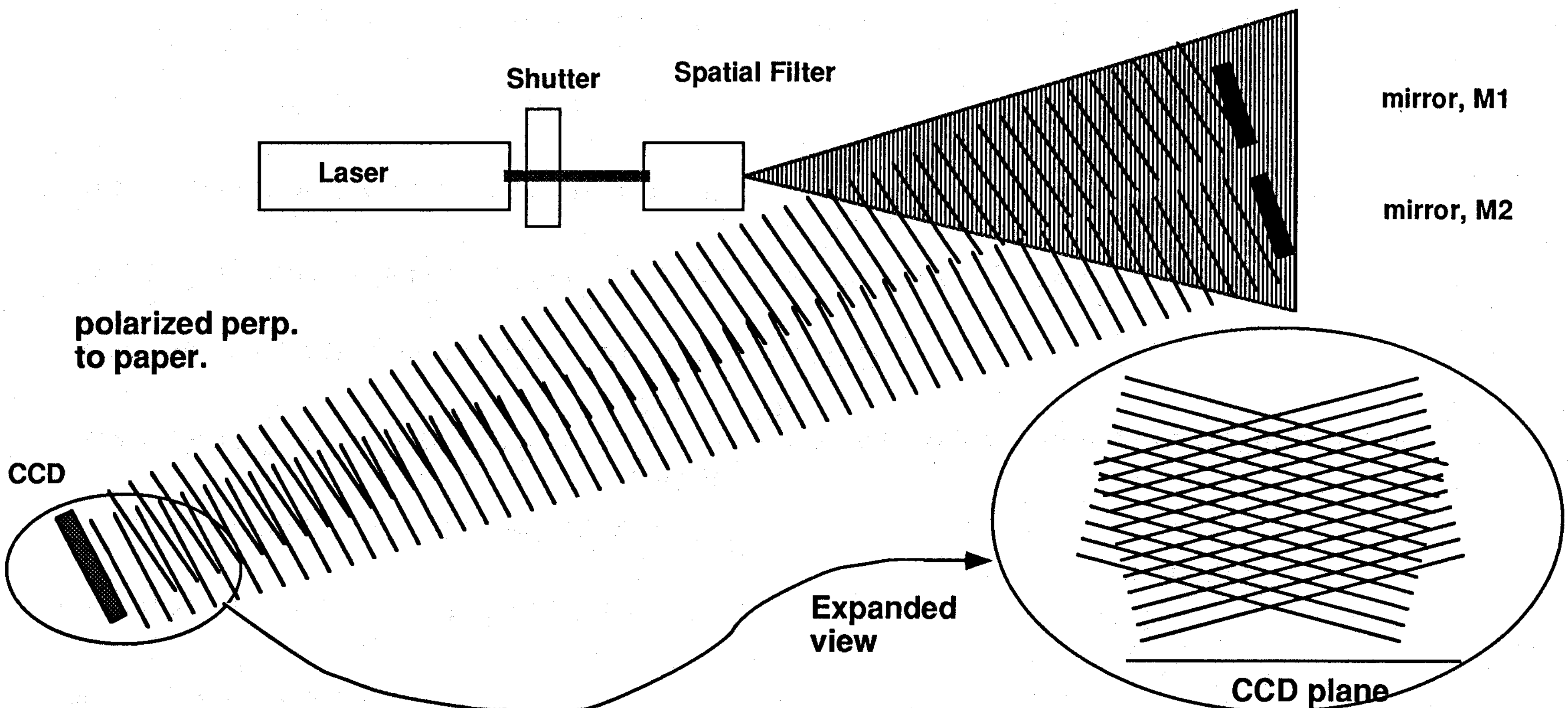
Interferometric MTF Measurement Apparatus



For details, see Ostrovsky, Butusov, and Ostrovskaya, Interferometry by Holography, Springer Verlag, New York, 1980.

Expected Advantages:

1) >500/mm spatial frequencies at 100% modulation possible.
2) No precision alignment required (large depth of field).
3) Full imager can be characterised (large field of view).
4) Perturbations effect all spatial frequencies
   to roughly the same extent.
5) Frequency and response spectrally well defined.

Concern:

1) Coherent illumination effects
2) Polarized light artifacts.
3) Finite field curvature
(correctable, if needed)

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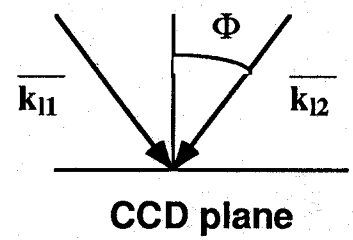
Interferometric MTF Measurement Technique

Establish geometry for desired spatial frequency: $k_s = k_l \sin(\Phi)$ where ks and kl are the wavenumbers of the light and the grating and Φ is the half angle between the two beams. This assumes the resultant wave is normally incident on the detector, which does not have to be the case.



Obtain interferogram, I.

Obtain image with mirror 2 blocked, A1.

Obtain image with mirror 1 blocked, A2.

Create normalized interferogram $F = \frac{I - A1 - A2}{\mathrm{sqrt}(A1 * A2)}$ to minimize effects of amplitude variations.

(similar to a coherence function modified by the CCD)

Fourier Transform F to determine exact spatial frequency and grating amplitude.

Inspect spectrum for anomalous components.

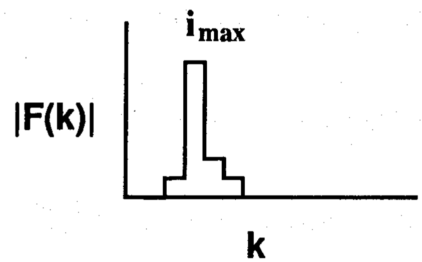
Repeat for other spatial frequencies.

Normalize grating amplitudes to 1 at zero frequency, plot versus spatial frequency.
(Ideally, the normalization is not required since the amplitude modulation should be 100%.)

Spectrum Analysis Details

- Fourier Transform F: $$F(k_i)=\sum_{l=0}^{511} f(x_l)e^{jk_ix_l}$$

- Find the peak power location, i_{max}



Care must be taken to determine if the grating is aliased.

- Find the total power in a bandwidth 2m around the peak , take square root:

$$P=\sqrt{\sum_{i=i_{max}-m}^{i_{max}+m} F^2(k_i)}$$

- Determine P for each grating frequency. Normalize P to 1 at zero frequency

- A plot of P versus grating frequency (i_{max}) is the MTF curve.

For example, see Oppenheim and Schafer, Digital Signal Processing.

Note: For these results, m=4. This was a good compromise between including noise power and excluding grating power which sampling artifacts spread in frequency space. For MTF's over a few percent, the choice of m is not too critical.

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Experimental Results

Imager: Kaf-1400 , Eastman Kodak Company.
Following data obtained from line 300, pixels 100-611.

Pixel Size: 6.8um

Nyquist rate: 74/mm

Temperature: room temperature, unregulated

Drive conditions: nominal values from KAF-1400 data sheet.

Illumination: 6328A from an Aerotech HeNe laser.

Illumination Angle: variable, almost normally incident.

Exposure times: variable, from 0.1 to 5 seconds.

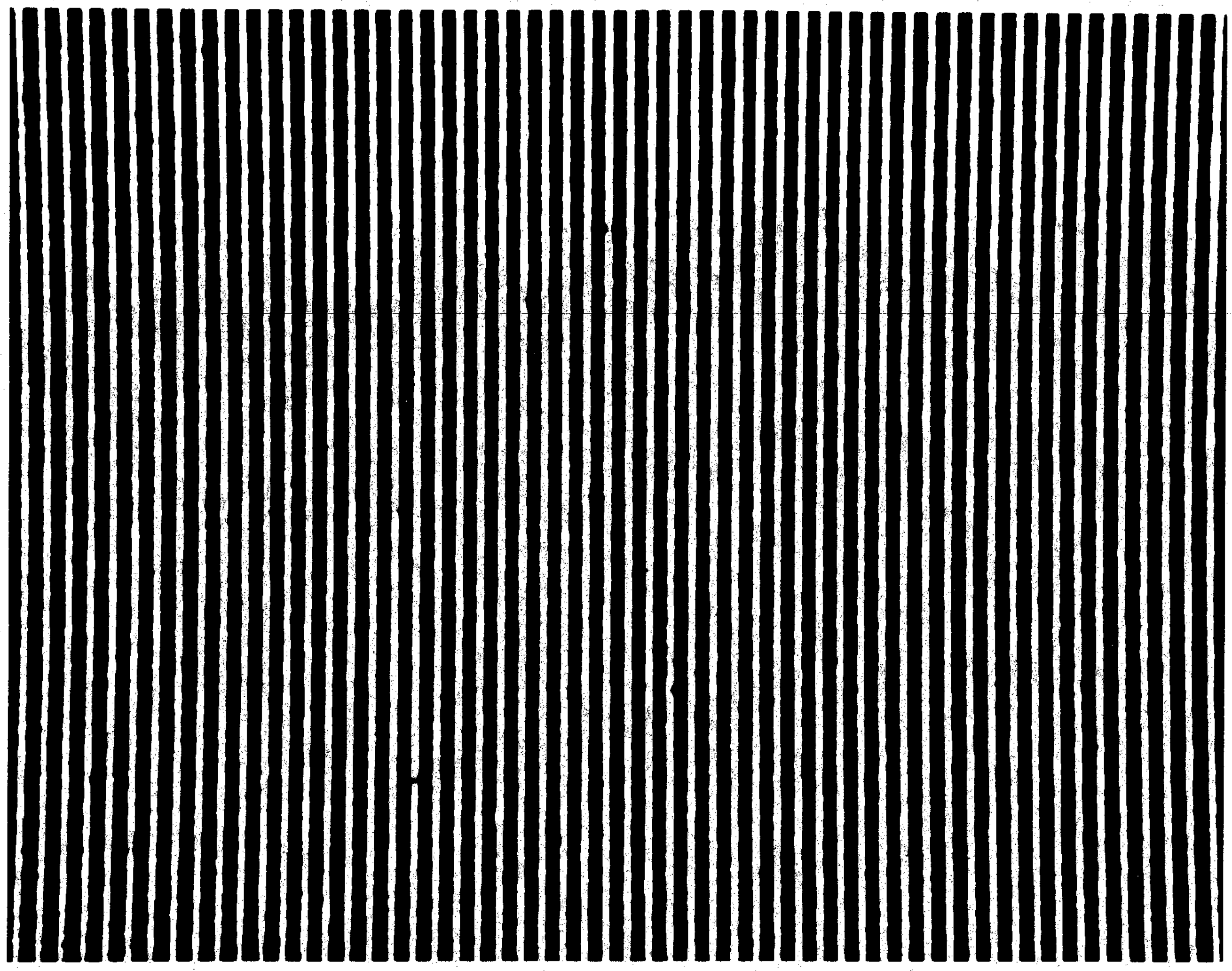
Exposure level: variable, between 1000 and 15000 electrons average signal.

Pixel Rate: 50khz.

Environment: well baffled with black honeycomb walls. Vibration isolated table.

Grating pattern parallel to channel stops to within about 1% (10 pixels across 1000 pixels).
(curvature was minimized)

Sample Interference Grating



This photograph illustrates a typical grating pattern with spatial frequency approximately 100/mm.Clear, straight striations are observable but the sinusoidal purity is not. The original photograph was made on Kodak 2415 film and developed in Kodak D-19. This view was obtained through a microscope. The original negative does function as a good transmission grating.

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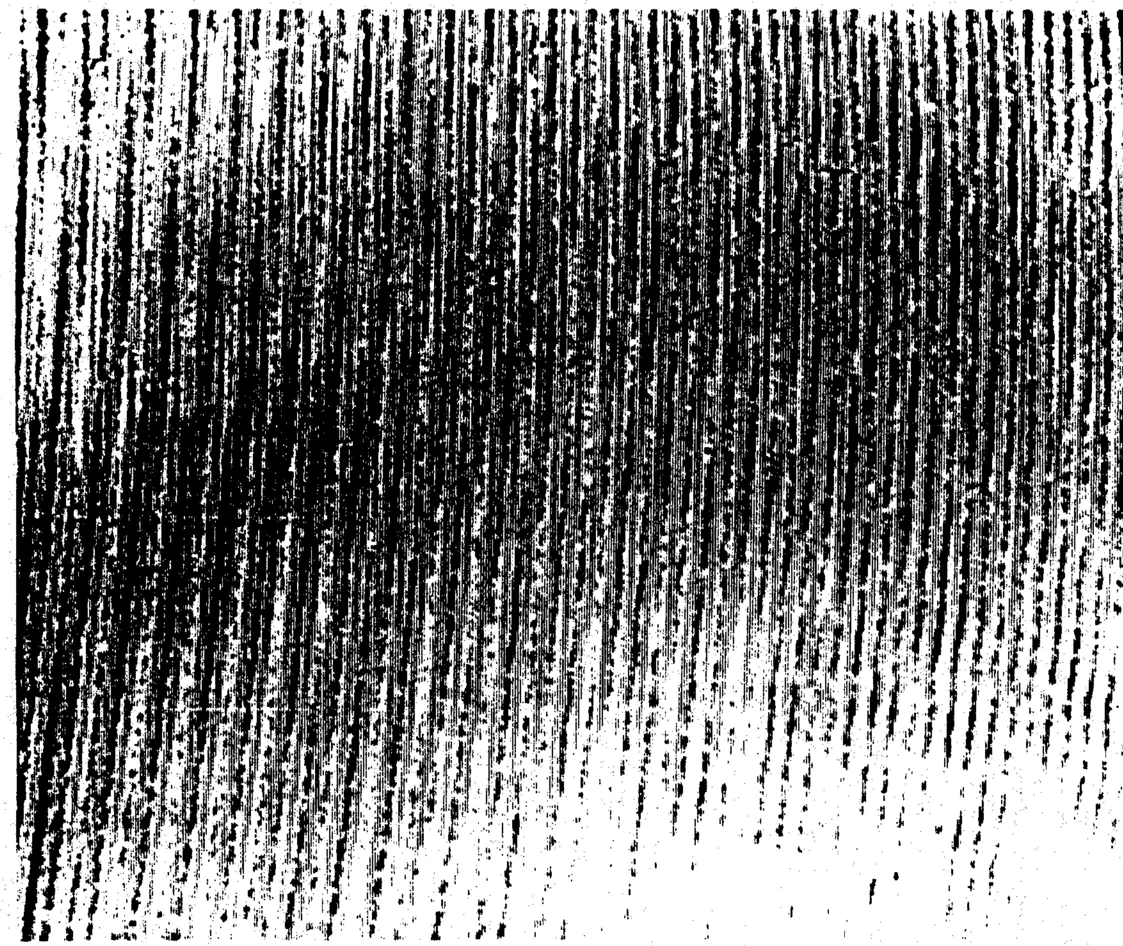
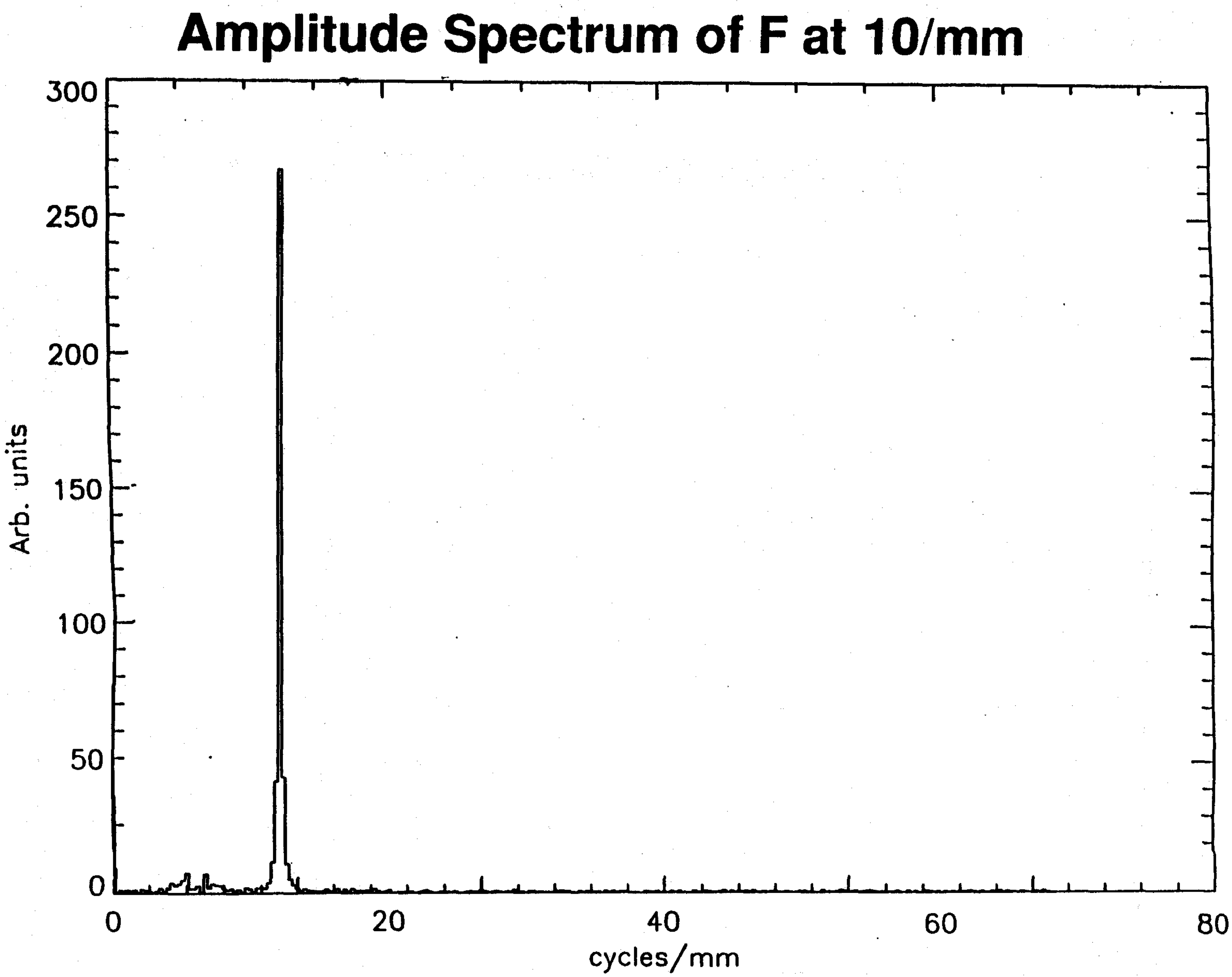
Raw Interferogram Near Nyquist

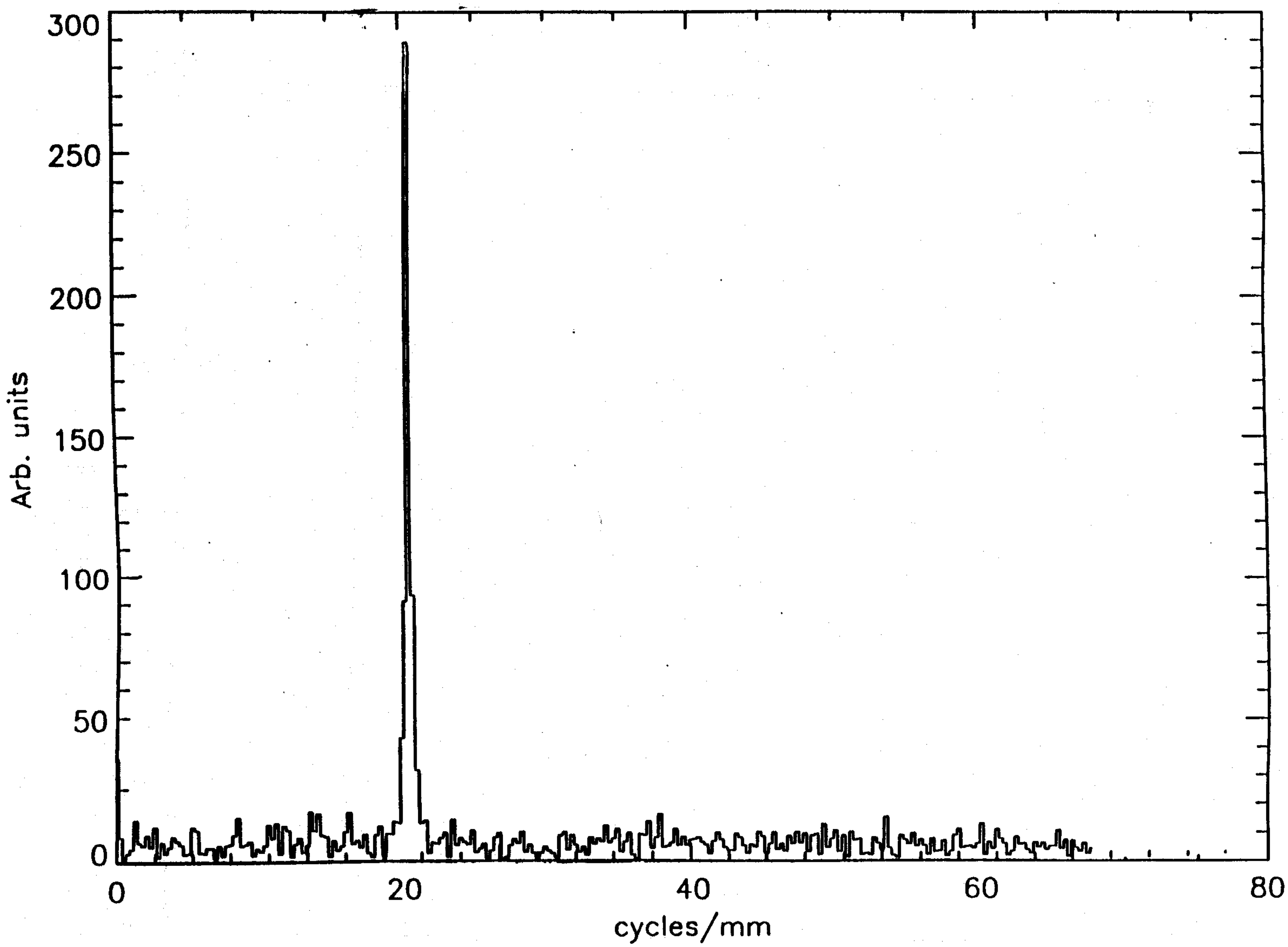


Grating striations are observed beating against the CCD sampling rate. The grating frequency is just above the Nyquist rate. The grating is slightly mis-aligned with respect to the imager and some field curvature is seen. However, the grating does allow MTF measurement at any point on the CCD.



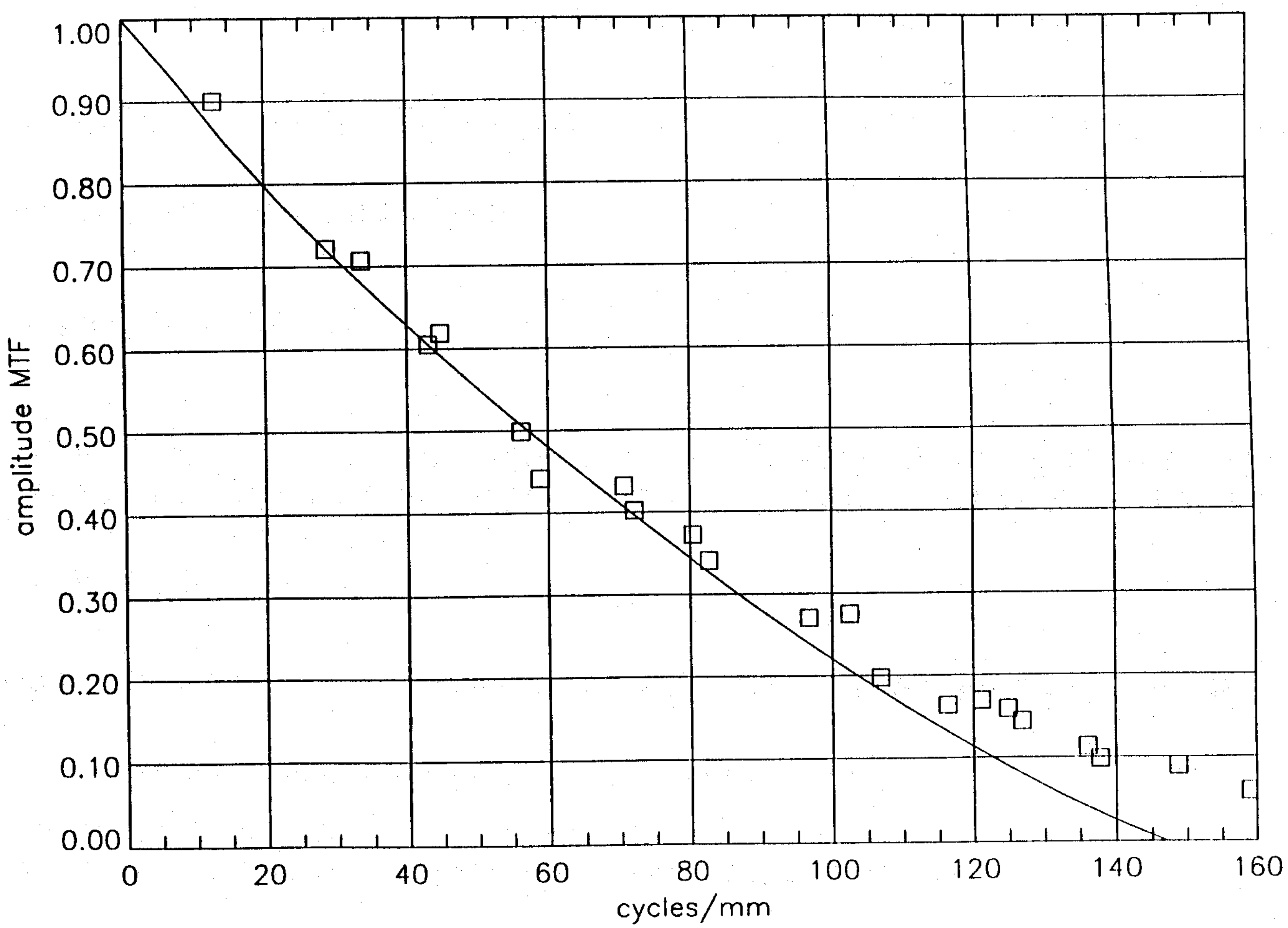
A pure, single peak is seen at the grating frequency. Harmonic distortion and amplitude modulation are unmeasureable. The low freqency noise that is seen here was later attributed to diffraction from the beam block used to obtain images A1 and A2. The DC amplitude is about 10 units.

Amplitude Spectrum at 126/mm



The grating frequency is still well above the system noise even though the MTF is only 15%. The DC component is 35 units. Apparently, the noise floor limits the minimum measurable MTF to ≈2%. The x-axis is correct, this peak has aliased since it is close to twice the Nyquist rate.

KAF-1400 MTF



The measured data (boxes) fit well with a simple model accounting for the pixel aperture and charge diffusion (solid line). No parameters have been adjusted to fit the experimental points. The apparent noise in the data correlates with average signal level(1000 to 15000 electrons). It is not known if this is an artifact of the measurement. This plot was furnished courtesy of Eastman Kodak Co.

Conclusion

We have demonstrated:

- Reasonable agreement between measurement and simple model to over 100/mm , giving us confidence in this new method.
- No apparent problems exist due to coherent illumination.
- Depth of field and field of view are greatly improved over traditional optics.

We comment:

- Results are tentative, and will be repeated with tighter control on variables like average signal level, angle of incidence, stray light, and beam block artifacts.

Under Development:

- Better FFT analysis algorithms.
- Observation of MTF degradation due to CTI at low and near-full well charge levels.
- Holographic dot arrays for direct point spread function measurement.

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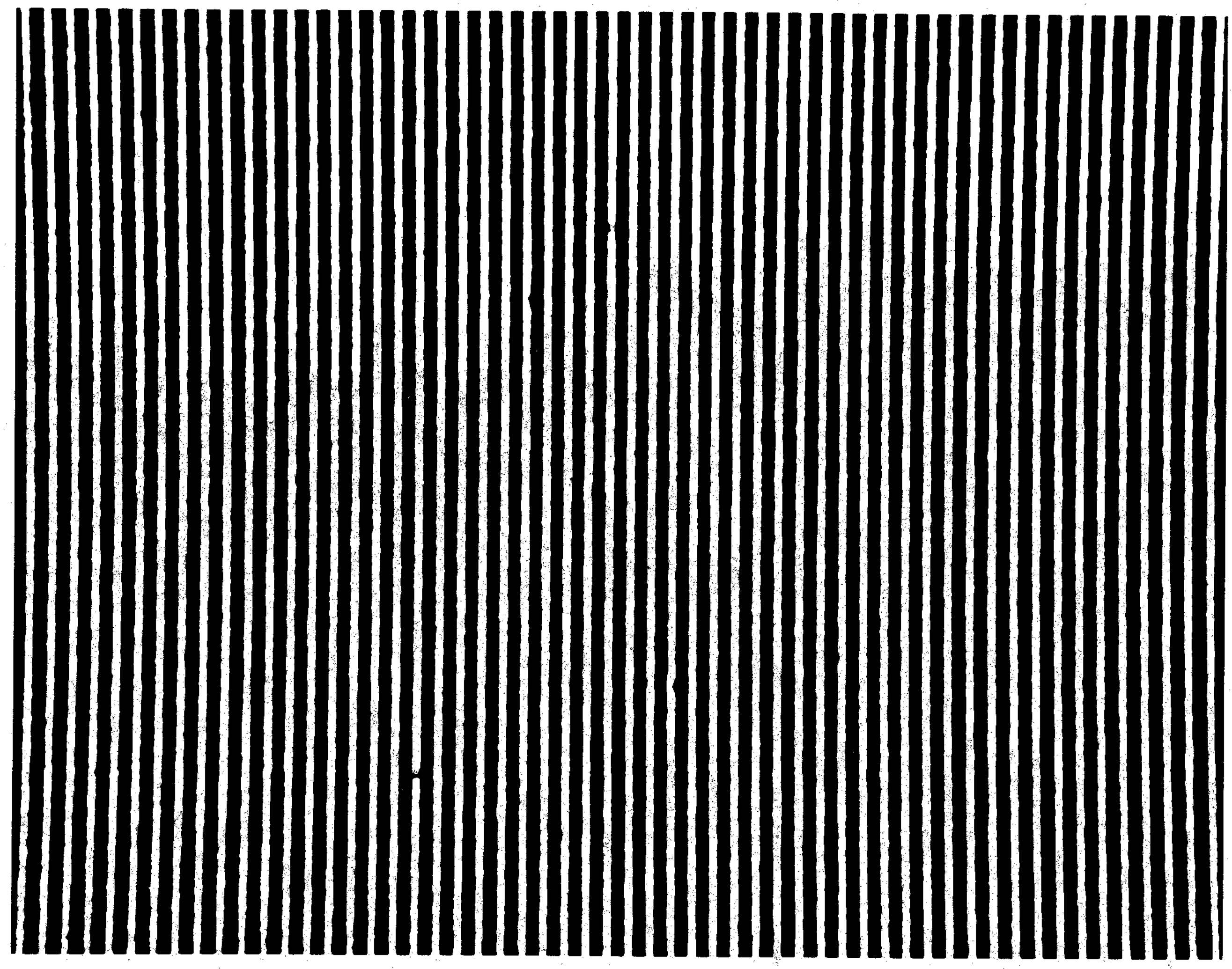

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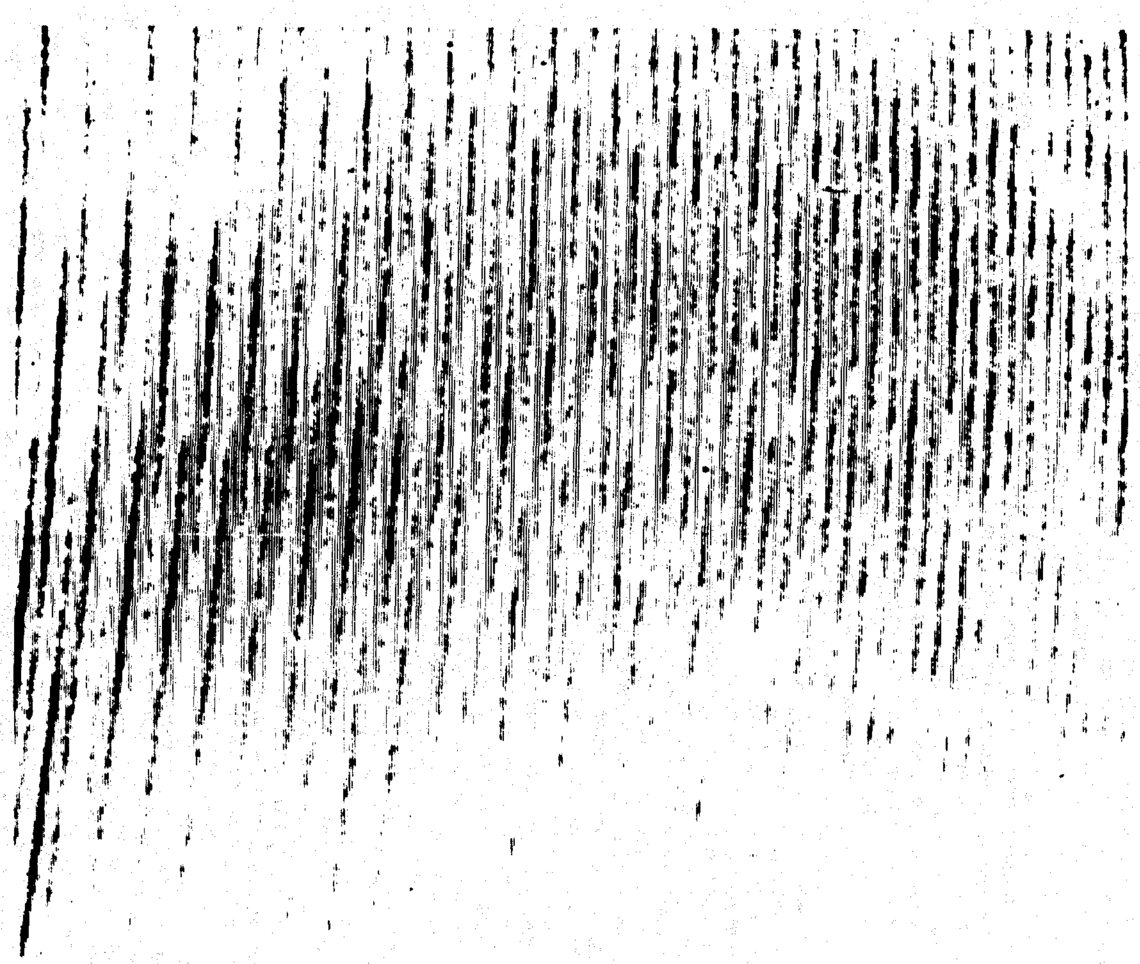

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ISSUES IN GLOBAL (PIXEL-BY-PIXEL) CHARACTERIZATION

- GLOBAL CHARACTERIZATION IS A COMPLEX, EXPENSIVE TASK FOR EVEN MODERATE-SIZE CCD ARRAYS
- REQUREMENTS:
  - WELL-CORRECTED, WIDE-FIELD OPTICAL SYSTEM
  - SYSTEM FOR TRANSLATING (AREA ARRAYS) OR SCANNING (TDI CCD'S) MULTI-FREQUENCY BAR PATTERNS ACROSS EACH PIXEL IN THE ARRAY
  - LARGE DATA CAPTURE AND REDUCTION SYSTEM
  - MEANINGFUL METHOD OF DISPLAYING AND TABULATING PER PIXEL MTF DATA AND ASSOCIATED STATISTICS (E.G. IMAGE PROCESSING TECHNIQUES)
- AVOID PIXEL-BY-PIXEL CHARACTERIZATION WHERE POSSIBLE

SUMMARY/CONCLUSIONS

- CCD MTF IS USEFUL FIGURE-OF-MERIT WHEN MEASURED VERSUS SPATIAL FREQUENCY AND COLOR
- HIGH-QUALITY, CHARACTERIZED OPTICAL SYSTEM NEEDED FOR CREDIBLE MTF MEASUREMENTS
  - OPTICS MTF SHOULD BE MEASURED VERSUS FIELD POSITION AND COLOR
- FOR TDI CCD'S, IMAGE-TO-CCD ELECTRONIC SCAN VELOCITY SYNCHRONIZATION AND ALIGNMENT ARE CRITICAL:
  - MEASUREMENT SYSTEM MUST PROVIDE REQUIRED CONTROL
- GLOBAL (PER PIXEL) CHARACTERIZATION OF CCD ARRAY'S IS A COMPLEX TASK REQUIRING ADVANCED EXPERIMENTAL SET-UP, DATA ACQUISITION, DATA REDUCTION AND DISPLAY SYSTEMS.