

Modulation Transfer Function (MTF) of CCD Imagers Utility, Models, and Measurement Methods

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Introduction

- **MODULATION TRANSFER FUNCTION (MTF) AND POINT-SPREAD-FUNCTION (PSF) ARE OFTEN-USED FIGURES OF MERIT FOR DESCRIBING (IN PART) THE RESOLVING CAPABILITY OF ELECTRO-OPTICAL (EO) SENSOR SYSTEMS**

MTF
↑
RESOLUTION DESCRIBED
IN THE SPATIAL FREQUENCY
DOMAIN (lp/mm)

—————→ **EO SYSTEMS WHICH IMAGE EXTENDED SOURCES (camera systems, document copiers, etc.)**

PSF
↑
RESOLUTION DESCRIBED
IN THE SPATIAL DOMAIN: PSF
IS THE SPATIAL IMPULSE
RESPONSE FUNCTION

—————→ **EO SYSTEMS WHICH ARE USED FOR POINT-SOURCE DETECTION APPLICATIONS (star trackers, military earth-limb detection sensors, etc.)**

Utility and Interpretability of EO Imaging System Output

- IMAGE UTILITY AND INTERPRETABILITY DEPENDS, IN A COMPLEX, SUBJECTIVE WAY ON:

- TARGET CONTRAST

- EO DETECTION AND DISPLAY SYSTEM MTF

} DEPEND ON SPATIAL
FREQUENCY

- THRESHOLD MODULATION (TM) NEEDED FOR HUMAN OR AUTOMATIC SYSTEM DETECTION TO SEE A MINIMUM MODULATION DIFFERENCE

} DEPENDS ON SPATIAL
FREQUENCY AND SIGNAL-
TO-NOISE RATIO

- THE GROUND (or object) RESOLVED DISTANCE (GRD) IS A POPULAR DOWNLOOKING IMAGE SENSOR FIGURE OF MERIT:

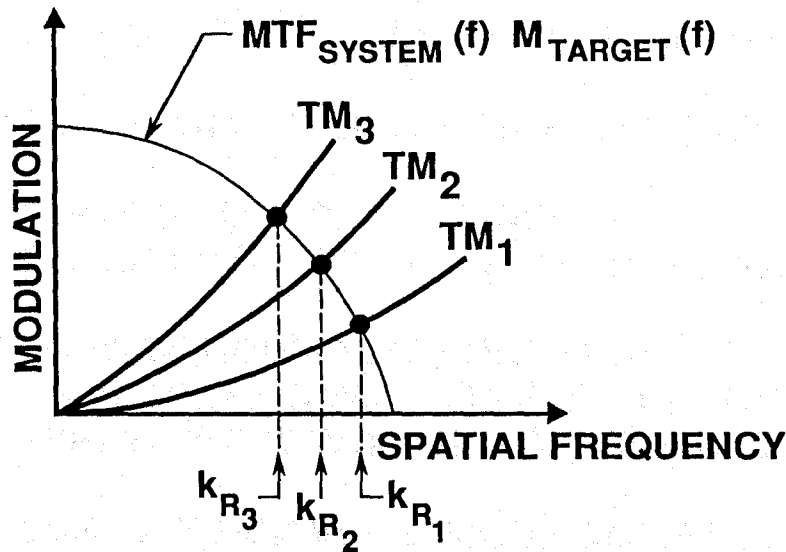
- GRD \equiv MINIMUM TEST TARGET "LINE-PAIR" RESOLVED IN OBJECT SPACE

- $k_R \equiv 1/GRD$; k_R IS THE MAXIMUM SPATIAL FREQUENCY THAT CAN BE RESOLVED

- TWO PIXEL ARE NEEDED TO RESOLVE A TEST TARGET LINE-PAIR AT NYQUIST

- TYPICALLY GRD $\approx 2 \times$ PIXEL PITCH FOR A PROPERLY DESIGNED EO IMAGING SYSTEM

Maximum-Resolved Frequency (f_R) for an EO Imaging System*



- TM (threshold modulation) $\sim \frac{1}{SNR(f)}$
- SNR_{min} AND HENCE TM CURVES INCREASE MONOTONICALLY WITH SPATIAL FREQUENCY
- $k_R = 1/GRD$

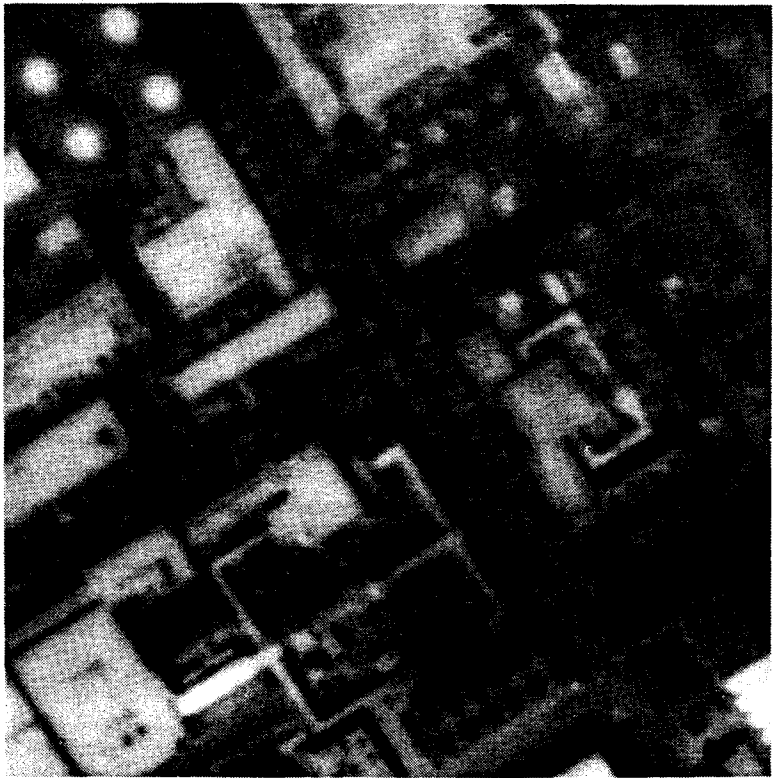
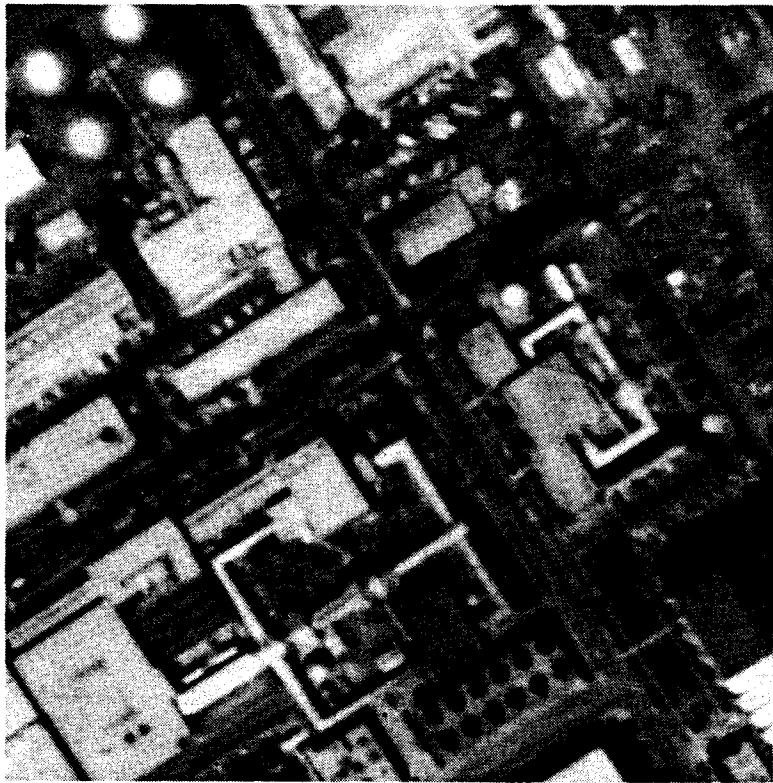
- COMBINE SINGLE-PIXEL SIGNAL AND NOISE WITH SYSTEM MTF AND TARGET MODULATION TO DETERMINE k_R (MAXIMUM-RESOLVED-FREQUENCY) OR GRD

- k_R OR GRD BECOME "SINGLE-POINT" FIGURES OF MERIT FOR DESCRIBING IMAGING SYSTEM RESOLVING CAPABILITY

– USEFUL FOR ANSWERING THE QUESTION:

"CAN AN EO IMAGING SYSTEM RESOLVE A BAR-TARGET WITH MODULATION, M_{TARGET} , AT A SPATIAL FREQUENCY, k ?"

* R. Lyon, et al., Proceedings of the SPIE, Vol 79, pp 216 – 227, 1976



Other EO Imaging System Figures of Merit and Evaluation Approaches (Cont'd)

- USE DETAILED EO SYSTEM 2D IMAGE SIMULATION APPROACH* WITH CORRECTLY MODELLED:
 - 2D SYSTEM POLYCHROMATIC MTF
 - SENSOR SIGNAL AND NOISE
 - OFFSET/GAIN NONUNIFORMITIES
 - ILLUMINATION AND SENSOR VIEWING GEOMETRY
- REQUIRES APPROPRIATE HIGH-RESOLUTION INPUT SCENE \rightarrow 2D FOURIER TRANSFORM OF INPUT SCENE \times 2D SYSTEM MTF \rightarrow 2D INVERSE FOURIER TRANSFORM \rightarrow PIXEL SAMPLING

DIRECT EVALUATION OF SIMULATED EXTENDED IMAGERY

- k_R AND GRD CAN BE EXTRACTED FROM "SIMULATED" INPUT-BAR-PATTERN SCENE

* T. S. Lomheim and L. S. Kalman, "Analytical Modelling and Digital Simulation of Scanning Charge-Coupled Device Imaging Systems", Chapter 14, Electro-Optical Displays, M. Karim, Ed., Marcel-Dekker, Nov 1991

Utility of MTF as an Imaging System Figure of Merit

- **EO IMAGING SYSTEM MTF MUST BE DESCRIBED AND CHARACTERIZED:**
 - AS A FUNCTION OF SPATIAL FREQUENCY
(not just at Nyquist)
 - IN TWO DIMENSIONS (k_x, k_y)
 - AS A FUNCTION OF OPTICAL WAVELENGTH
 - WITH PIXEL SAMPLING EFFECTS CONSIDERED (aliasing)

**TO BE USEFUL AS A PREDICTIVE TOOL IN IMAGING
SENSOR DESIGN.**

MTF BASICS

MTF MODELS

MTF Basics

- THE OPTICAL TRANSFER FUNCTION (OTF) AND PSF FORM A FOURIER-TRANSFORM PAIR*

$$\text{OTF}(k_x, k_y) = \text{FT}\{\text{PSF}(x, y)\}$$

$$\text{PSF}(x, y) = \text{FT}^{-1}\{\text{OTF}(k_x, k_y)\}$$

- $\text{MTF}(k_x, k_y) = |\text{OTF}(k_x, k_y)|$

– IN INCOHERENT IMAGING SYSTEMS USING WELL-CORRECTED OPTICS, PHASE EFFECTS OF THE MTF CAN USUALLY BE IGNORED

- MTF AND PSF CONTAIN THE SAME INFORMATION, BUT IN DIFFERENT DOMAINS

- USE OF MTF/PSF IMPLIES ASSUMPTION OF LINEAR SYSTEM:

– SYSTEM PSF = CONVOLUTION OF SUBSYSTEM OR COMPONENT PSFs

– SYSTEM MTF = PRODUCT OF SUBSYSTEM OR COMPONENT MTFs

* J. W. Goodman, Introduction to Fourier Optics, McGraw-Hill, 1968

Scanning TDI-CCD Sensor 2D MTF Component Equations

	$k \equiv$ SPATIAL FREQUENCY; TYPICALLY IN $\mu\text{p/mm}$ $\text{SINC} \equiv \frac{\text{SIN } \pi x}{\pi x}$ AND $x \equiv$ CROSS-SCAN $y \equiv$ IN-SCAN	
A. DETECTOR SPATIAL APERTURE (Trapezoidal) B. DETECTOR TEMPORAL APERTURE/SMEAR (J. F. Johnson and R. A. Keller)	$\text{MTF}_{\text{apt}}(k_x, k_y) = \text{MTF}_{\text{apt}}(k_x, \Delta x, \Delta S_x) \text{MTF}_{\text{apt}}(k_y, \Delta y, \Delta S_y)$ $\text{MTF}_{\text{apt}}(k, \Delta \ell, \Delta S_\ell) = \text{SINC}(k\Delta \ell) \text{SINC}[k(\Delta \ell - \Delta S_\ell)]$ $\text{MTF}_{\text{int}}(k_x, k_y) = \frac{\text{SINC}[N_{\text{TDI}}(k_x \Delta V_x + k_y \Delta V_y) T_{\text{int}}]}{\text{SINC}[(k_x \Delta V_x + k_y \Delta V_y) T_{\text{int}} / N_{\text{ph}}]}$ $x \text{SINC}\left[\frac{k_x \Delta X + (k_x \Delta V_x + k_y \Delta V_y) T_{\text{int}}}{N_{\text{ph}}}\right]$	$\Delta X, \Delta Y =$ PIXEL WIDTH (x, y) $\Delta S_x, \Delta S_y =$ PIXEL FLAT-RESPONSE WIDTH (x, y) $N_{\text{TDI}} =$ # TDI STAGES $\Delta V_x =$ VELOCITY ERROR: X-DIRECTION $\Delta V_y =$ VELOCITY ERROR: Y-DIRECTION $T_{\text{int}} =$ INTEGRATION TIME $N_{\text{ph}} =$ # CLOCK PHASES/PIXEL $\alpha =$ ABSORPTION COEFFICIENT OF SILICON AT λ
C. CARRIER DIFFUSION (Sieb, IEEE Trans on Electron Devices, Vol ED-21, p 210, 1974)	$\text{MTF}_{\text{diff}}(k_x, k_y, \lambda) = \frac{1 - \left[\frac{\exp(-\alpha L_{\text{dep}} \ell)}{1 + \alpha L} \right]}{1 - \left[\frac{\exp(-\alpha L_{\text{depl}})}{1 + \alpha L_{\text{diff}}} \right]}$ $L = \frac{L_{\text{diff}}}{\sqrt{1 + 4\pi^2 L_{\text{diff}}^2 k^2}}; k^2 = k_x^2 + k_y^2; L_{\text{diff}} = \sqrt{D\tau}$	$\Delta V_y =$ VELOCITY ERROR: Y-DIRECTION $T_{\text{int}} =$ INTEGRATION TIME $N_{\text{ph}} =$ # CLOCK PHASES/PIXEL $\alpha =$ ABSORPTION COEFFICIENT OF SILICON AT λ
D. OPTICAL DIFFRACTION (E. L. O'Neill, JOSA, Vol 46, p 285, 1956)	$\text{MTF}_{\text{opt}}(k_x, k_y, \lambda)$ and $k = \sqrt{k_x^2 + k_y^2}$ (use O'Neill formula if optics is diffraction limited)	$L_{\text{dep}} \ell =$ CCD DEPLETION WIDTH
E. OPTICAL DEGRADATION (D. Nicholson, Proc of SPIE Vol 54, p 163, 1975)	$\text{MTF}_{\text{od}}(k_x, k_y, \lambda)$ and $k = \sqrt{k_x^2 + k_y^2}$ (use Nicholson equations)	$L_{\text{diff}} =$ DIFFUSION LENGTH
COMPOSITE SYSTEM MTF:		
F. $\text{MTF}_{\text{total}}(k_x, k_y) = \text{MTF}_{\text{apt}}(k_x, k_y) \text{MTF}_{\text{int}}(k_x, k_y) \text{MTF}_{\text{diff}}(k_x, k_y) \text{MTF}_{\text{opt}}(k_x, k_y) \text{MTF}_{\text{od}}(k_x, k_y)$ TRUE AT A λ	ONE SAMPLE/DWELL ASSUMED IN THE IN-SCAN DIRECTION	

2D MTF Components: Temporal Integration and TDI Velocity Mismatch

- $$MTF_{Int}(k_x, k_y) = \frac{\text{SINC} [N_{TDI} (k_x \Delta V_x + k_y \Delta V_y) T_{Int}]}{\text{SINC} [(k_x \Delta V_x + k_y \Delta V_y) T_{Int} / N_{ph}]} \cdot \text{SINC} \left[\frac{k_x \Delta X + (k_x \Delta V_x + k_y \Delta V_y) T_{Int}}{N_{ph}} \right]$$

(after J. F. Johnson and R. A. Keller, The Aerospace Corp)

- If $\Delta V_y = 0$, NO CROSS-SCAN DRIFT-VELOCITY AND $k_y = 0$ THEN IN-SCAN MTF IS:

$$MTF_{Int}(k_x, 0) = \underbrace{\frac{\text{SINC}(N_{TDI} k_x \Delta V_x T_{Int})}{\text{SINC}(k_x \Delta V_x T_{Int} / N_{ph})}}_{\text{VELOCITY MISMATCH MTF}} \cdot \underbrace{\text{SINC} \left(\frac{k_x \Delta X}{N_{ph}} + \frac{k_x \Delta V_x T_{Int}}{N_{ph}} \right)}_{\text{TEMPORAL INTEGRATION MTF DUE TO DISCRETE CHARGE MOTION; PER CLOCK PHASE}}$$

SMALL (usually)

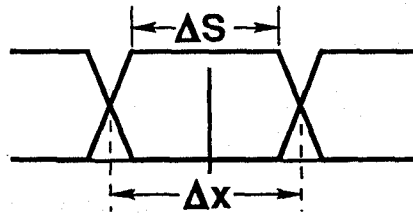
- If $f_x = 0$, CROSS-SCAN MTF IS:

$$MTF(0, k_y) = \text{SINC}(N_{TDI} k_y \Delta V_y T_{Int})$$

NOTE THAT EXCEPT FOR SPECIAL CASES, $MTF_{Int}(k_x, k_y) \neq MTF_{Int}(k_x, 0) \cdot MTF_{Int}(0, k_y)$

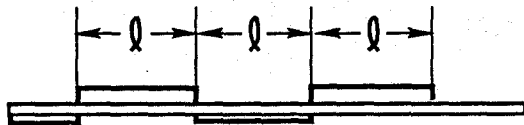
2D MTF Components: Detector Aperture

TRAPEZOIDAL APERTURE

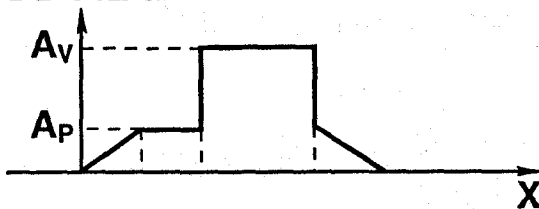


$$MTF = \text{SINC}(k\Delta x) \text{SINC}[k(\Delta x - \Delta S)]$$

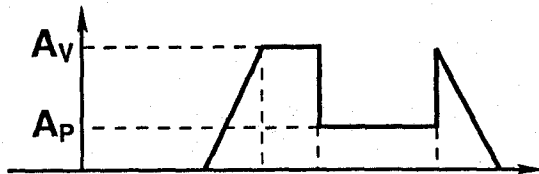
PATTERNED-ELECTRODE APERTURE RESPONSE (after Hosack, IEEE Trans on Elect Device, Vol Ed-28, p 53, 1981) ODD-FIELD/EVEN-FIELD VIRTUAL PHASE CCD



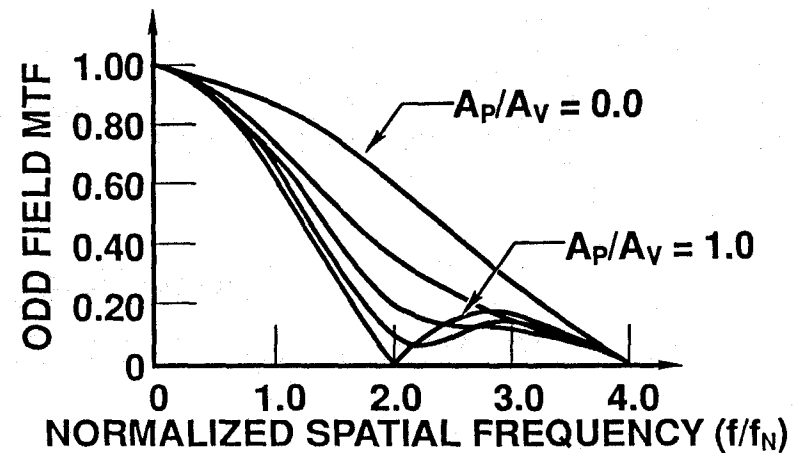
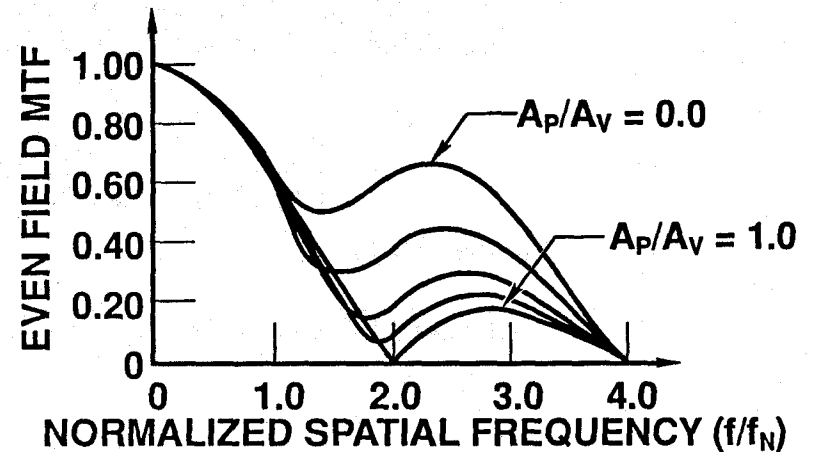
CELL N RESPONSE
ODD FIELD



CELL N RESPONSE
EVEN FIELD



$A_p/A_v = 1.0$
GIVES
TRAPEZOIDAL
APERTURE
RESPONSE



2D MTF Components: Carrier Diffusion

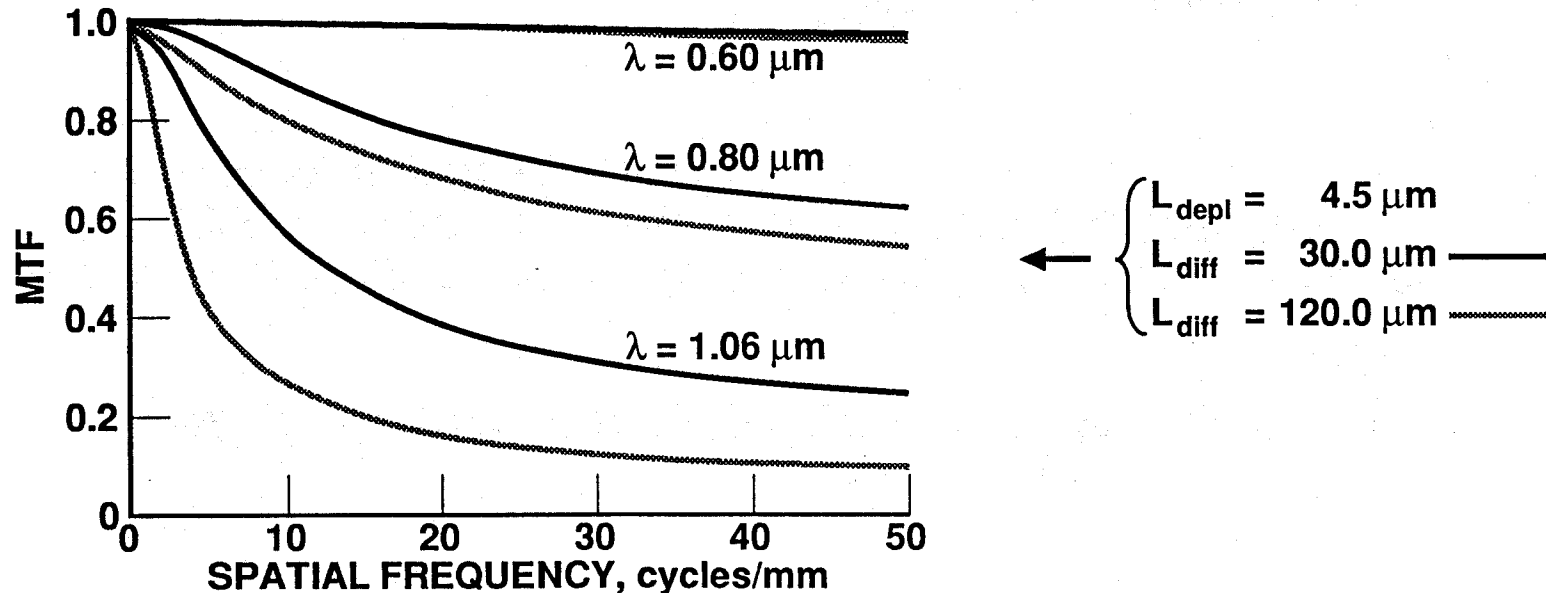
- SIEB MODEL TREATS CARRIER-DIFFUSION IN 2D USING DIFFUSION EQUATION WITH APPROPRIATE BOUNDARY CONDITIONS AND SINUSOIDAL GENERATION TERM

$$\text{MTF}_{\text{diff}}(k_x, k_y, \lambda) = \frac{1 - \left[\frac{\exp(-\alpha L_{\text{depl}})}{1 + \alpha L} \right]}{1 - \left[\frac{\exp(-\alpha L_{\text{depl}})}{1 + \alpha L_{\text{diff}}} \right]} \quad ; \quad L = \frac{L_{\text{diff}}}{\sqrt{1 + 4\pi^2 L_{\text{diff}}^2 k^2}}$$

AND $k^2 = k_x^2 + k_y^2$

NOTE: WAVELENGTH DEPENDENCE COMES FROM WAVELENGTH DEPENDENCE OF SILICON ABSORPTION COEFFICIENT $\alpha = \alpha(\lambda)$

- IMPROVED NUMERICAL MODEL FOR CARRIER DIFFUSION PUBLISHED BY T. D. LEE, et al., IEEE TRANS ON ELECTRON DEVICES, VOL ED-19, p 1464, 1983



MTF Polychromatic Spectral Weighting

- MTF COMPUTED AT λ_i DISCRETE WAVELENGTHS ACROSS DESIRED SPECTRAL BAND AND THEN WEIGHTED TO DETERMINE POLYCHROMATIC MTF:

$$\text{MTF}(k_x, k_y, \Delta\lambda) = \frac{\sum_{i=1}^N \text{MTF}(k_x, k_y, \lambda_i) \beta(\lambda_i)}{\sum_{i=1}^N \beta(\lambda_i)}$$

- SPECTRAL WEIGHTING COEFFICIENTS = $\beta(\lambda_i)$ AT DISCRETE WAVELENGTHS λ_i AND

$$\beta(\lambda_i) \propto \lambda_i I_{\text{SPEC}}(\lambda_i) T_{\text{OP}}(\lambda_i) \eta_{\lambda}$$

$I_{\text{SPEC}}(\lambda)$ = SPECTRAL INPUT (~ Watts)

$T_{\text{OP}}(\lambda)$ = OPTICS TRANSMITTANCE

$\eta(\lambda)$ = DETECTOR QUANTUM EFFICIENCY

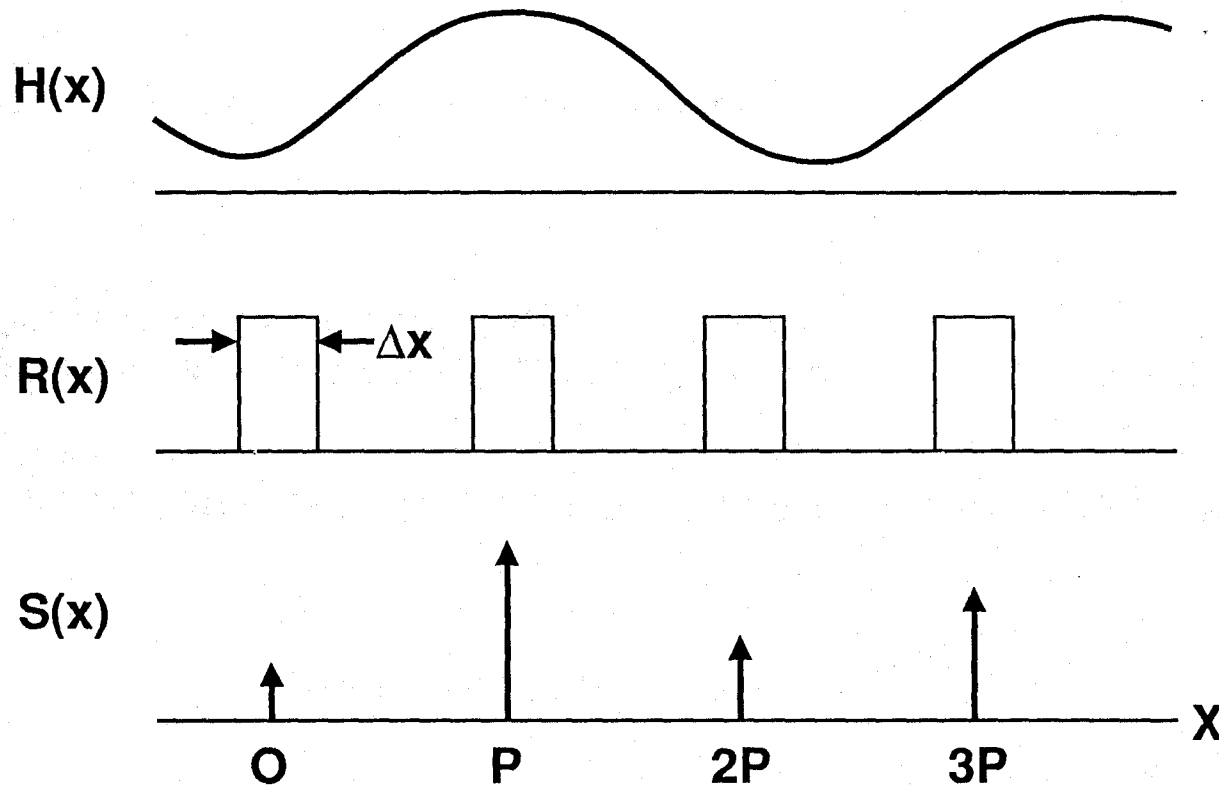
Spatial Sampling and Aliasing

- SPATIALLY-MODULATED INFORMATION ABOVE THE SAMPLING FREQUENCY, f_s , ($k_S = 1/\text{pixel pitch}$) NECESSARILY APPEARS IN THE $0 \rightarrow k_N$ REGION ($k_N = \text{Nyquist frequency}$)
- ALIASING BY A FREQUENCY $k > k_N$ OCCURS IN THE BAND $0 < k' < k_N$. k' IS GIVEN BY*

$$k = 2 m k_N \pm k', m = 1, 2, 3 \dots$$

- IF $k'_N = 10 \ell \text{ p/mm}$, YOU MIGHT GET CONTRIBUTIONS (aliased) FROM $2 k_N \pm 10$, $4 k_N \pm 10 \dots \ell \text{ p/mm}$
- DETAILED DISCUSSION OF CCD ALIASING IS FOUND IN H. HOSACK, IEEE TRANS ON ELECTRON DEVICES, VOL ED – 28, pp. 53-63, 1980

* N. Ahmed and T. Natarajan, Discrete Time Systems and Signals, Reston, Va, 1983, pp 123-125



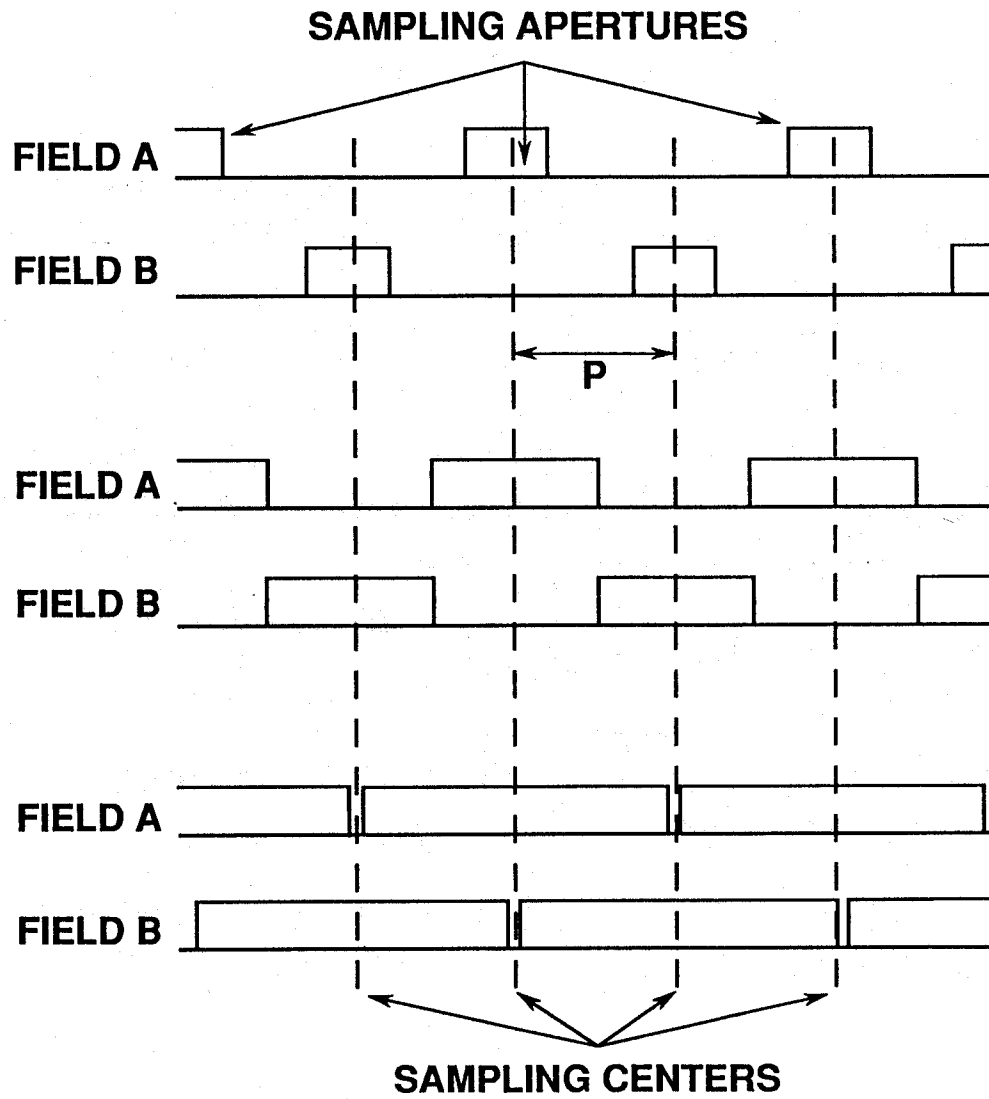
$H(x)$ = INPUT IRRADIANCE

$R(x)$ = APERTURE FUNCTION

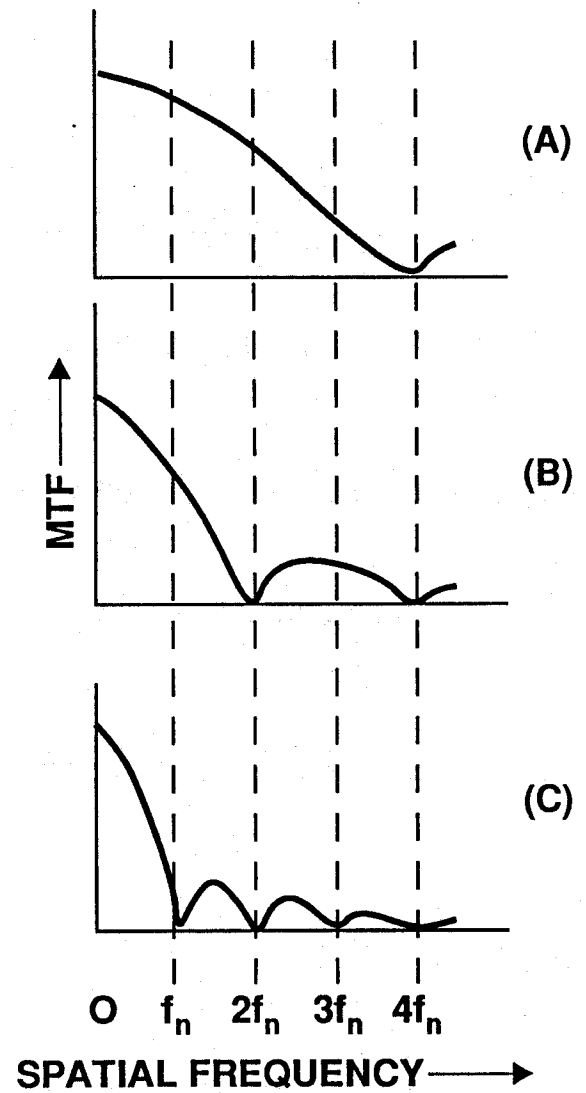
$S(x)$ = OUTPUT SIGNAL

MTF \equiv FOURIER - TRANSFORM
OF APERTURE
FUNCTION

$$\text{MTF} = \frac{\sin \frac{\pi \Delta x}{2P} \cdot \frac{k}{k_n}}{\frac{\pi \Delta x}{2P} \cdot \frac{k}{k}} , k_n \equiv \frac{1}{2P}$$



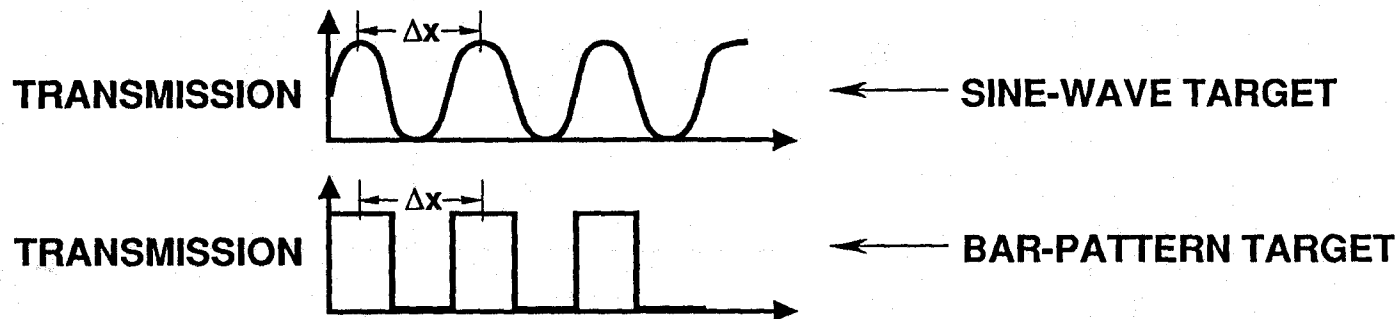
(a)



(b)

Contrast-Transfer-Function (CTF) and MTF

- BAR-PATTERN TARGETS ARE EASIER TO MANUFACTURE AND MORE PRACTICAL THAN "SINE-WAVE" PATTERN TARGETS



- CTF IS THE RESPONSE OF AN OPTICAL (or EO) TO BAR-PATTERN INPUTS OF VARYING SPATIAL FREQUENCY WHERE

$$CTF = \frac{CR - 1}{CR + 1} \quad \text{AND} \quad CR = \frac{I_{MAX}}{I_{MIN}} \text{ IS THE CONTRAST RATIO}$$

- SHARP EDGES IN BAR-TARGETS REQUIRE FOURIER SUPERPOSITION OF ODD-HARMONIC SINE-WAVES*

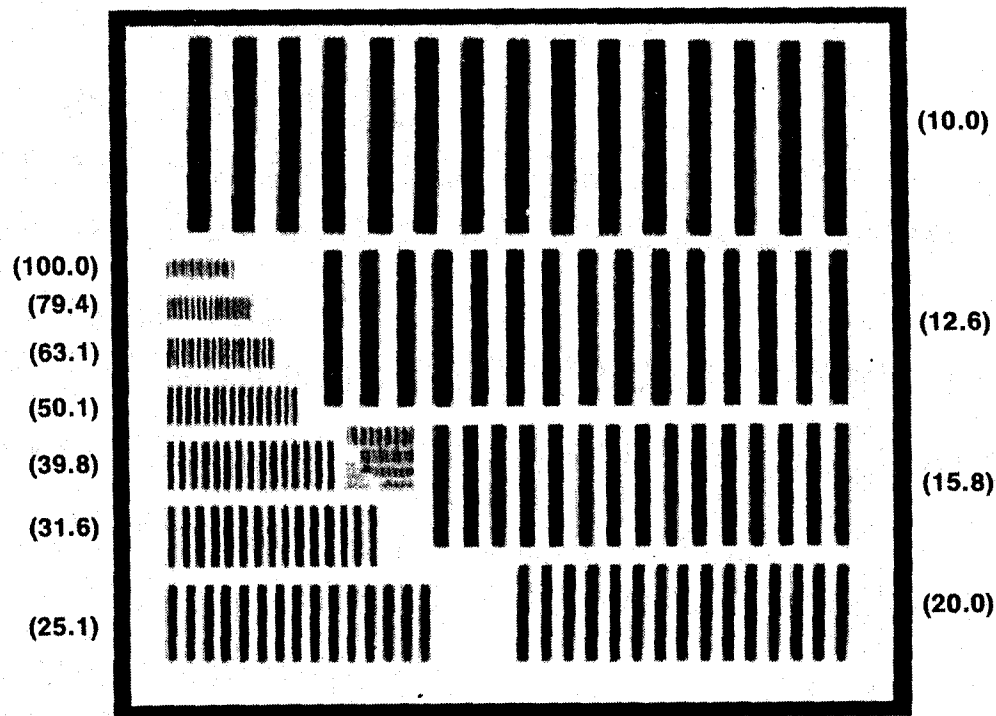
$$MTF(k) = \frac{\pi}{4} \left[CTF(k) + \frac{CTF(3k)}{3} - \frac{CTF(5k)}{5} + \frac{CTF(7k)}{7} + \dots \right]$$

* J. W. Coltman, J Opt Soc Am, Vol 44, pp 468-471 (1954)

CTF and MTF

- TO CONSTRUCT MTF AT A GIVEN SPATIAL FREQUENCY FROM CTF DATA REQUIRES:
 - USING CTF DATA AT AN INFINITE NUMBER OF HIGHER ODD-HARMONICS SPATIAL FREQUENCIES
 - THESE FREQUENCIES ARE MOSTLY ABOVE NYQUIST
 - ALIASING EFFECT MUST BE CONSIDERED; CAN USUALLY BE CIRCUMVENTED
 - MOST OPTIMIZED OPTICAL IMAGING SYSTEMS HAVE MTFs (AND CTFs) THAT "ROLL-OFF" RAPIDLY ABOVE THE NYQUIST FREQUENCY
 - * CORRECTIONS DUE TO HIGHER-ORDER FREQUENCY TERMS ARE LESS IMPORTANT
 - * $\frac{\pi}{4}$ LEADING TERM IS USUALLY MOST IMPORTANT CORRECTION

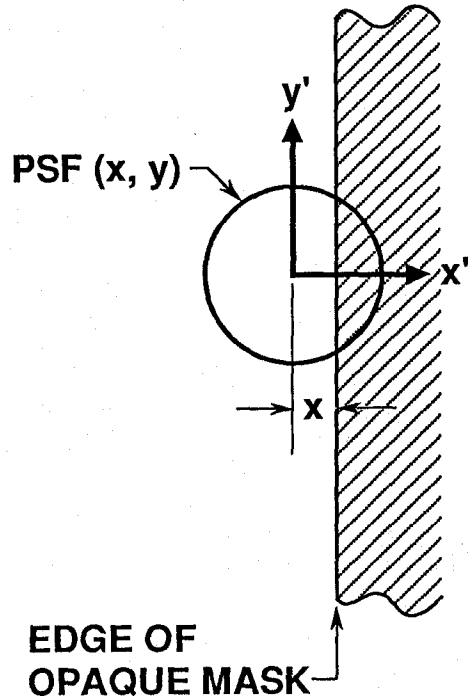
BAR-PATTERN SEQUENCE USED FOR CCD MTF CHARACTERIZATION



LABELED IN LINE PAIRS/MM

OPTICAL MTF MEASUREMENT DESCRIPTION

Relationship Between Point, Edge, Line-Spread Function*



EDGE-SPREAD FUNCTION

$$ESF(x) = \int_{-\infty}^x \int_{-\infty}^{\infty} PSF(x', y') dx' dy'$$

$$= PSF(x, y) \otimes U(x)$$

UNIT-STEP FUNCTION
(opaque mask edge)
2D CONVOLUTION

LINE-SPREAD FUNCTION

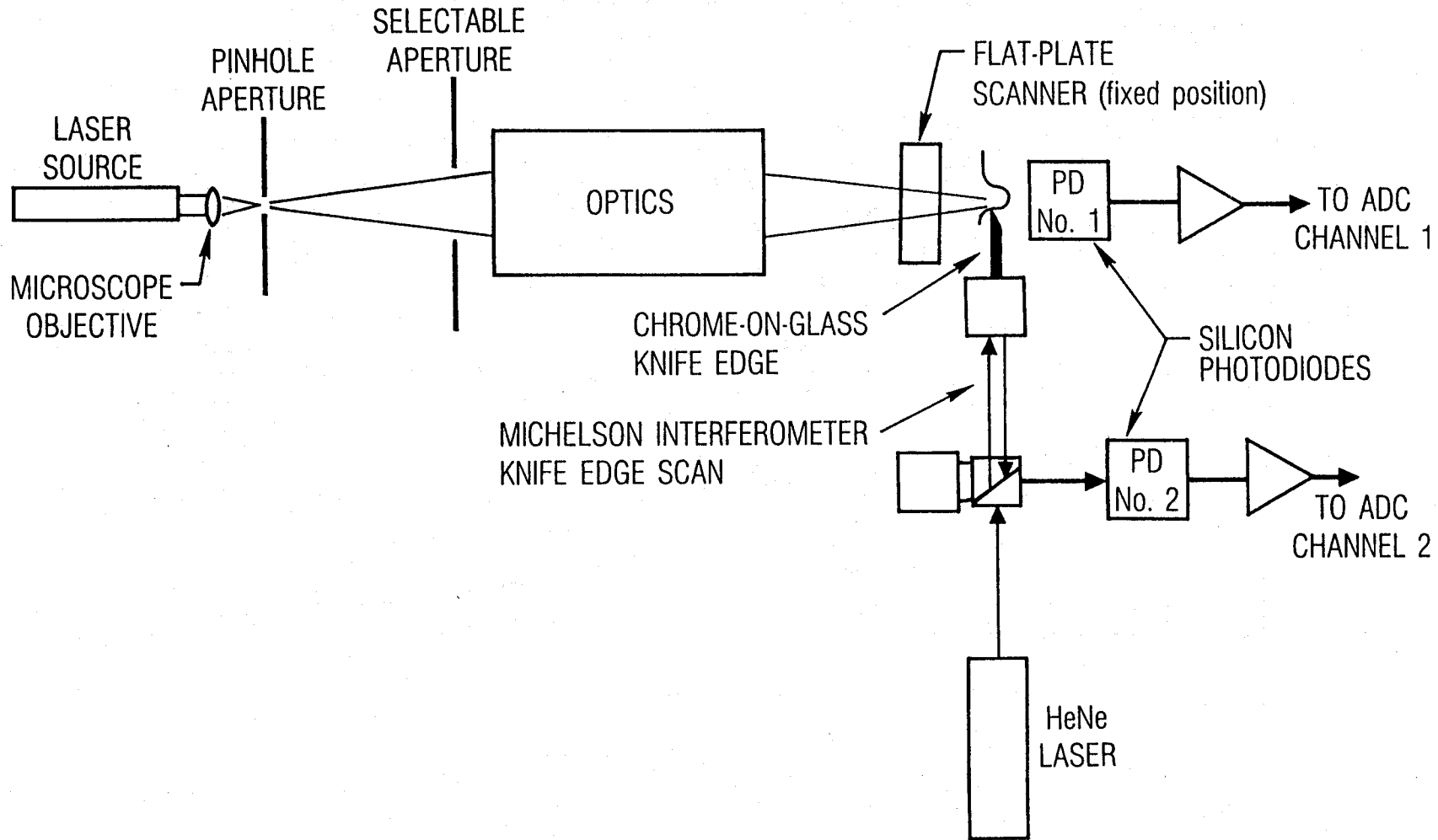
$$LSF(x) = \frac{d[ESF(x)]}{dx}$$

MTF IN X-DIRECTION

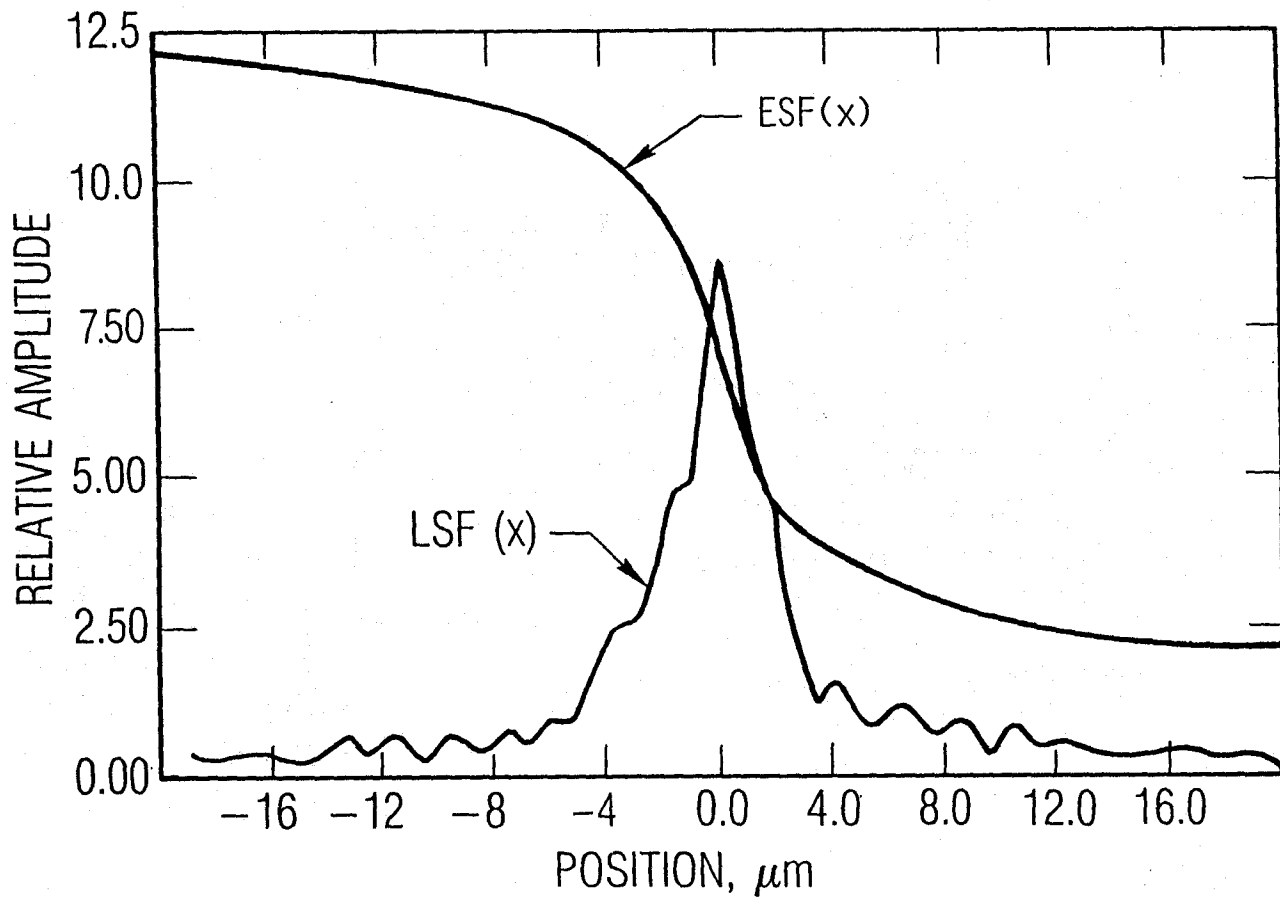
$$MTF(k_x) = FT\{LSF(x)\}$$

* L. W. Schumann and T. S. Lomheim, Applied Optics, Vol 28, pp 1703-1706, 1989
T. S. Lomheim et al, Optical Engineering, Vol 29, Section 4.3, pp 919-920, 1990

OPTICAL SCHEMATIC OF THE MICHELSON INTERFEROMETER-BASED KNIFE-EDGE
TECHNIQUE FOR MEASURING THE OPTICS MTF

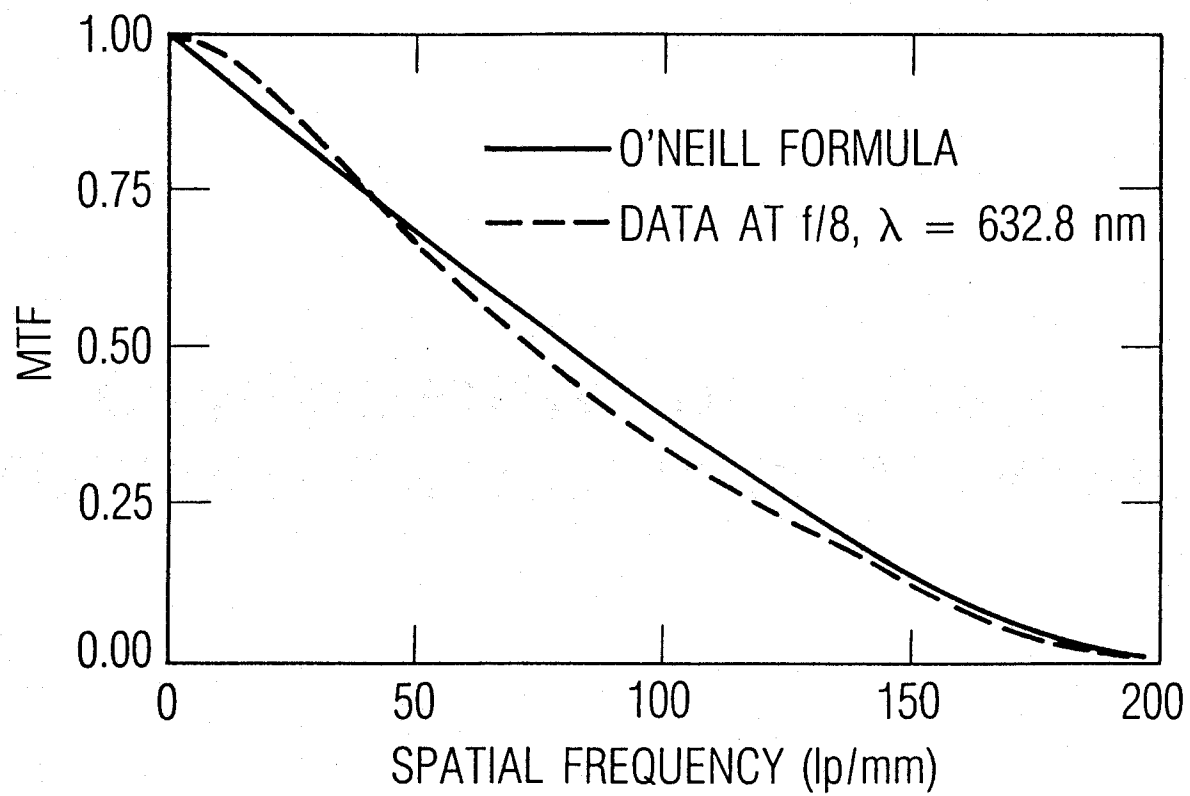


KNIFE-EDGE SCAN OF FOCUSED SPOT
OPTICAL MTF CHARACTERIZATION



MEASURED AND THEORETICAL MTFs FOR OPTICAL SYSTEM

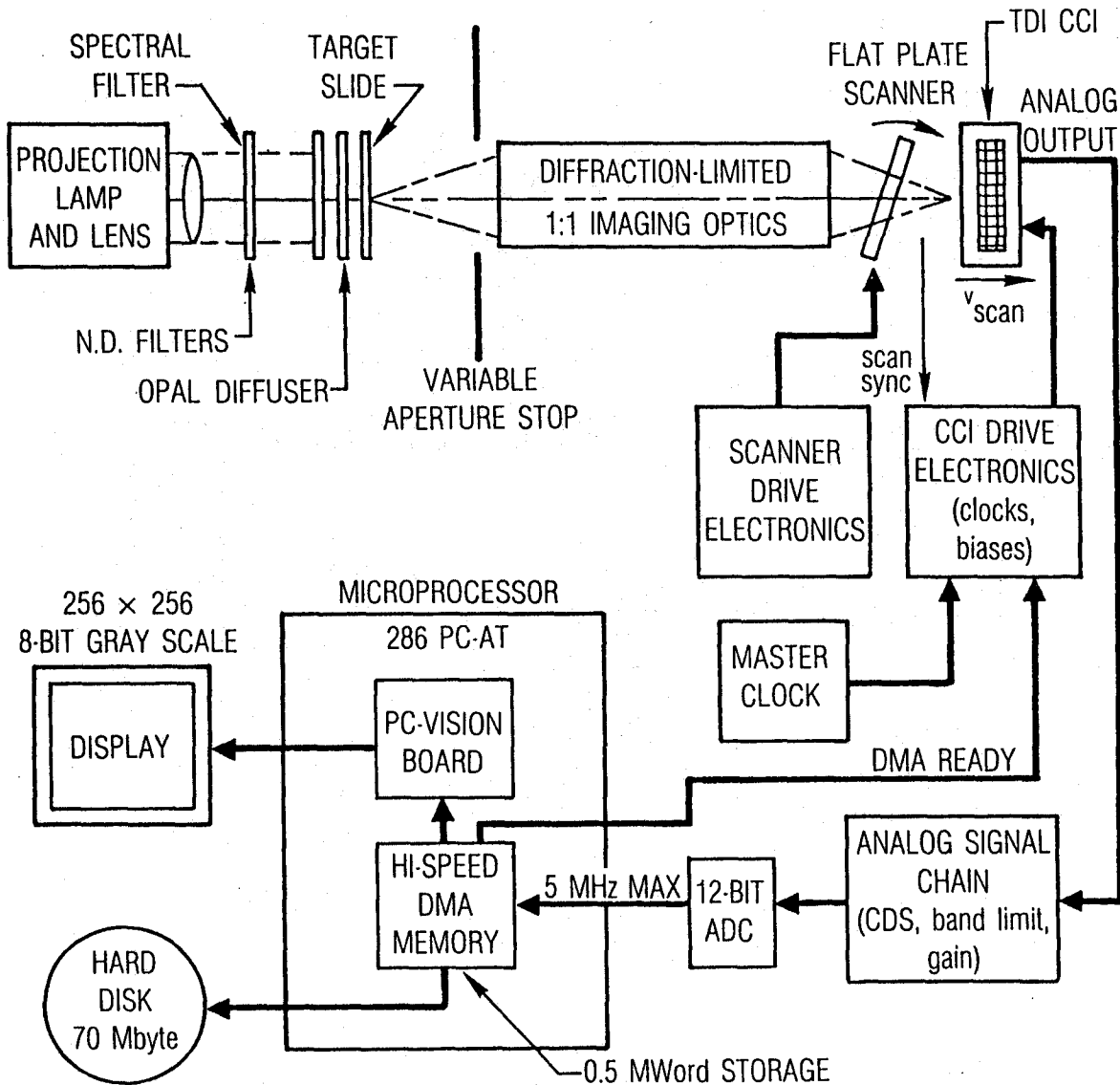
F#/8 AND $\lambda = 632.8$ nm



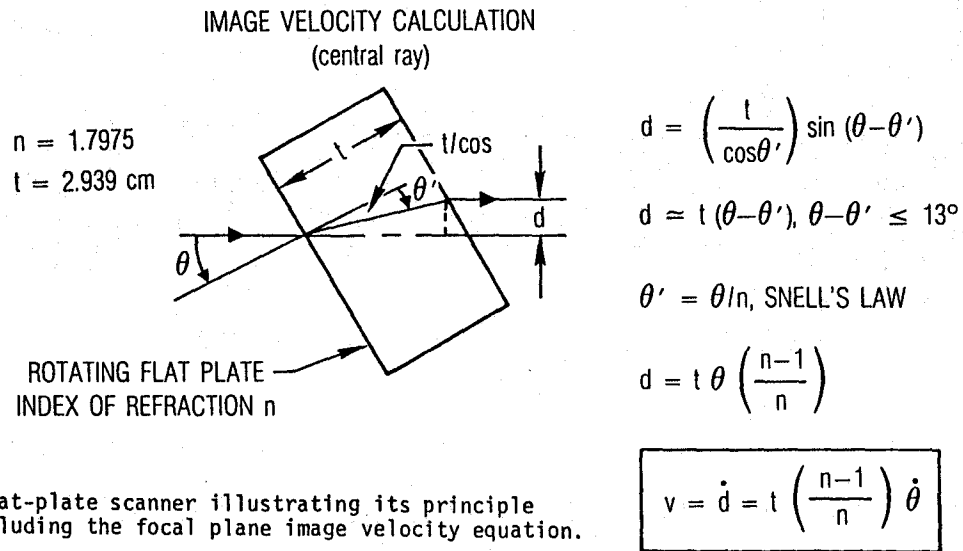
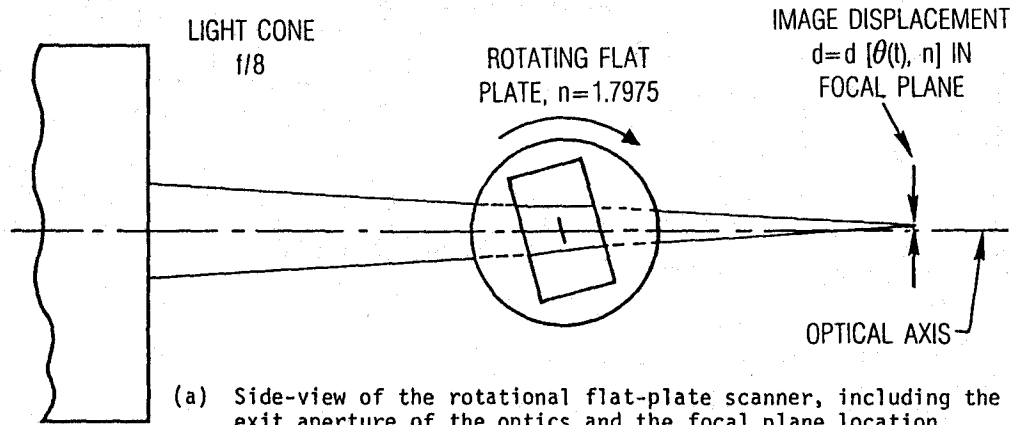
DESCRIPTION OF TDI-CCD SCANNER CHARACTERIZATION SYSTEM*

***T. S. Lomheim, et al., Optical Engineering, Vol 29, p 911, August 1990**

ELECTRO-OPTICAL SCANNING IMAGING SYSTEM USED FOR CHARACTERIZING TDI CCIs



ROTATING FLAT-PLATE SCANNER



PHASE-LOCKED LOOP ROTATION CONTROL

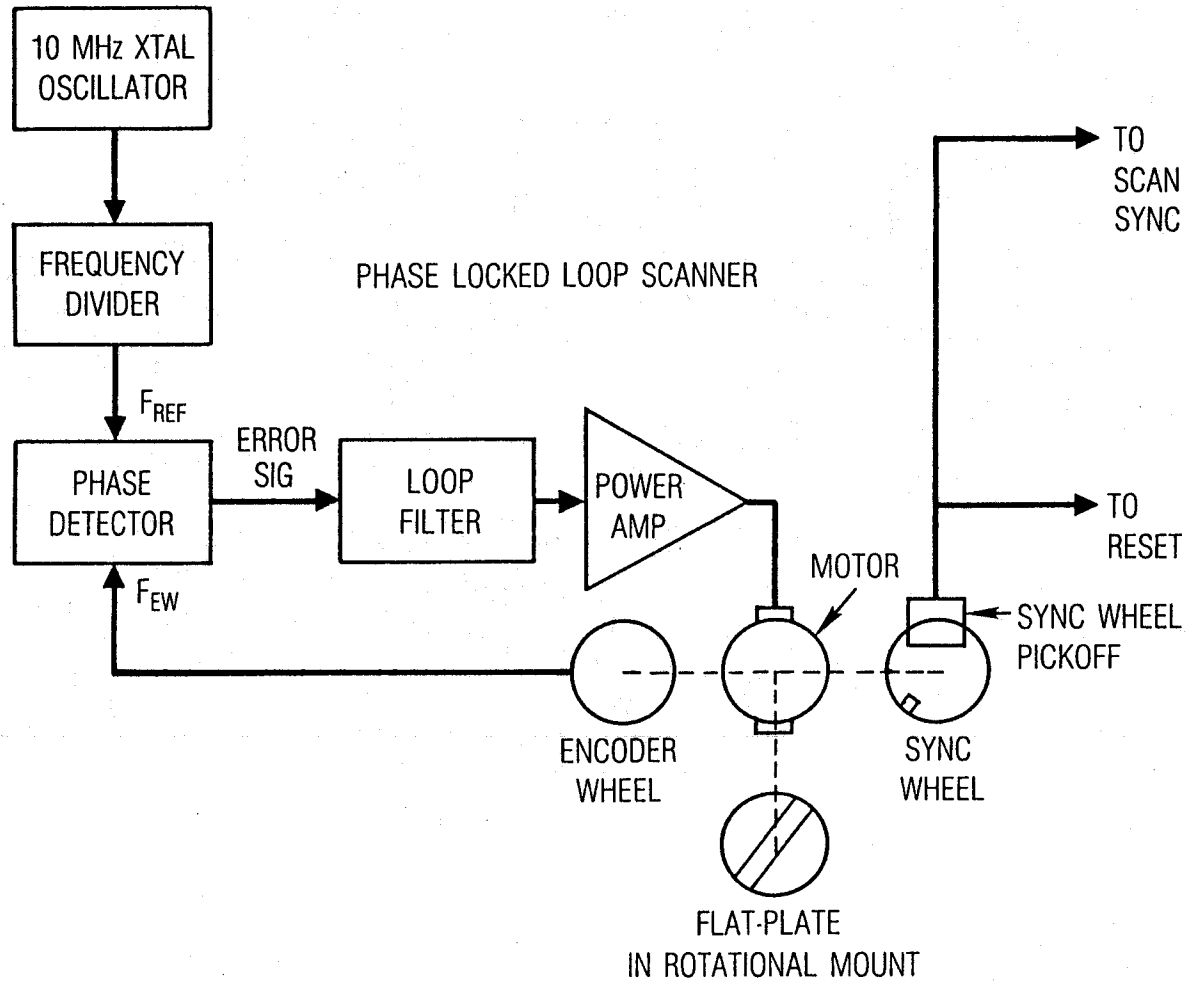
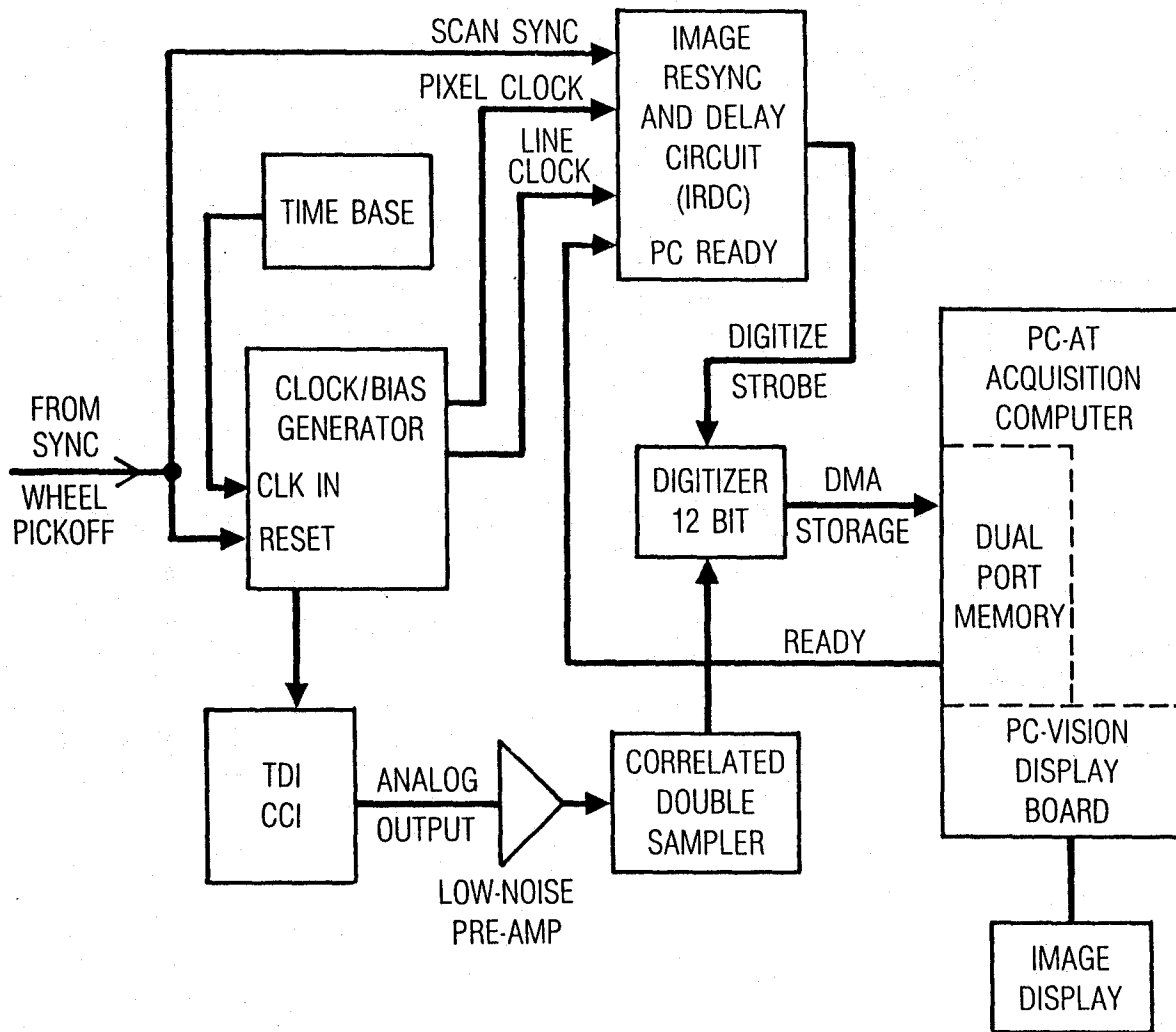
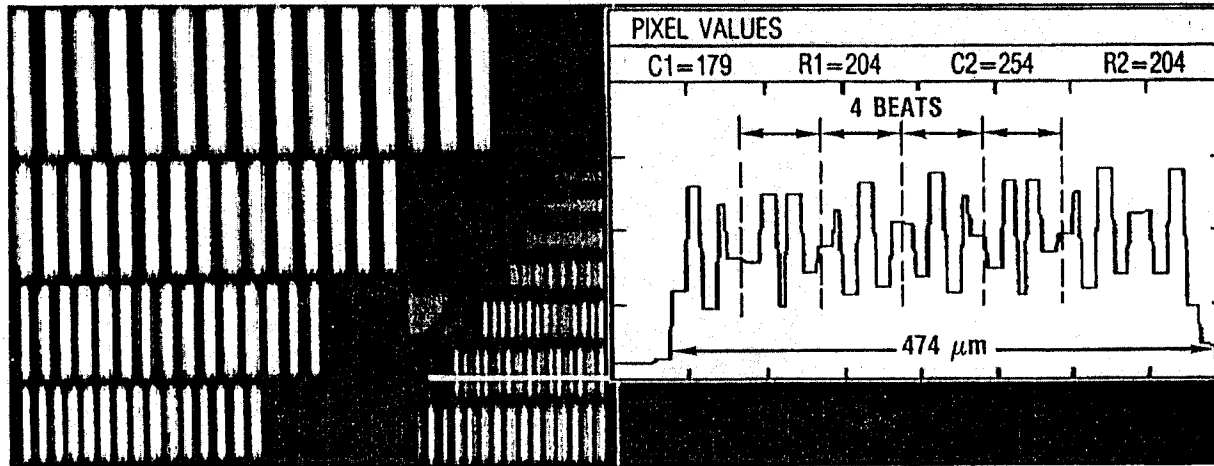


IMAGE-LINE SYNCHRONIZATION ELECTRONICS



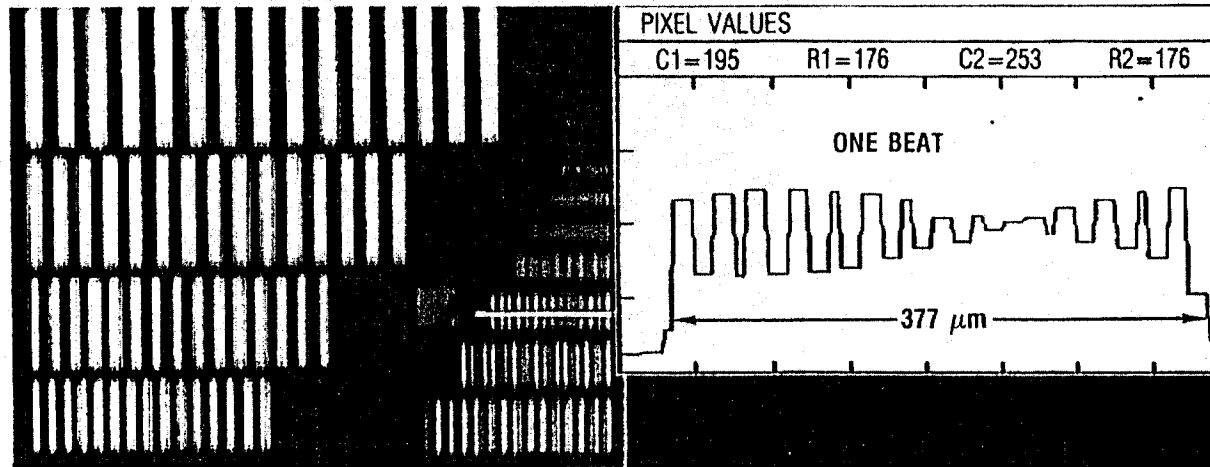
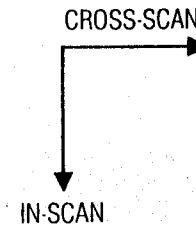
Cross-Scan Beat Patterns



$f_N = 38.46 \text{ lp/mm}$
 PATTERN 6 = 31.63 lp/mm

$f_{\text{BEAT}} = 6.83 \text{ lp/mm}$
 ONE BEAT = 5.6 PIXELS

PROFILE PLOT FOR BAR PATTERN 6 IS SHOWN
 BAR PATTERNS ARE IN THE CROSS-SCAN CONFIGURATION



PROFILE PLOT FOR BAR PATTERN 7
 PATTERN 7 = 39.82 lp/mm $f_{\text{BEAT}} = 1.36 \text{ lp/mm}$ ONE BEAT = 28.5 PIXELS

Velocity-Mismatch MTF: Setting Zeros IN SINC () TO SPECIFIC BAR PATTERNS

$$\text{sinc} \equiv \frac{\sin \pi x}{\pi x}$$

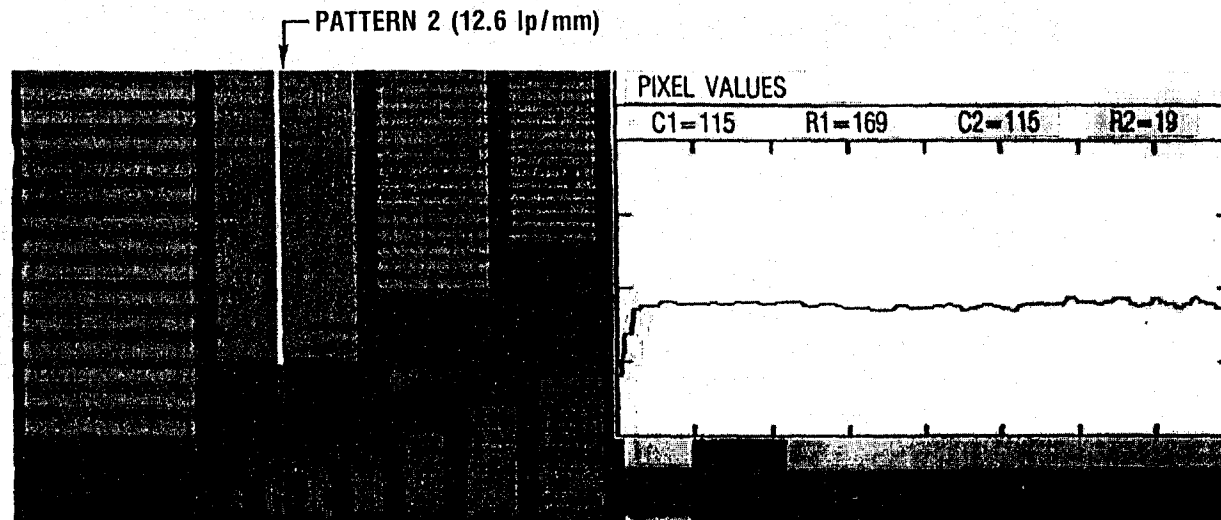
$$\text{sinc}(k N_{TDI} \Delta V_y T_{int}) = 0$$

$$\text{MTF} = 0$$

FOR

$$k_y = m / (N_{TDI} \Delta V_y T_{int})$$

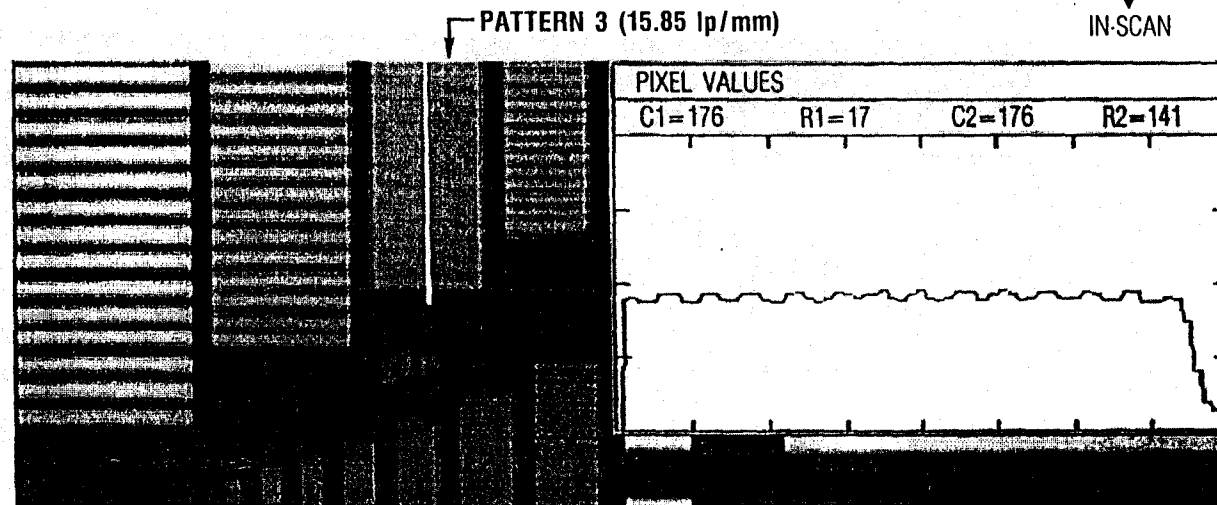
$$m = 1 \text{ (for this case)}$$



$\Delta V_{\text{MISMATCH}} = 0.00416$ m/sec. ZERO IN $\text{MTF}_{\text{MISMATCH}}$ OCCURS AT BAR PATTERN 2

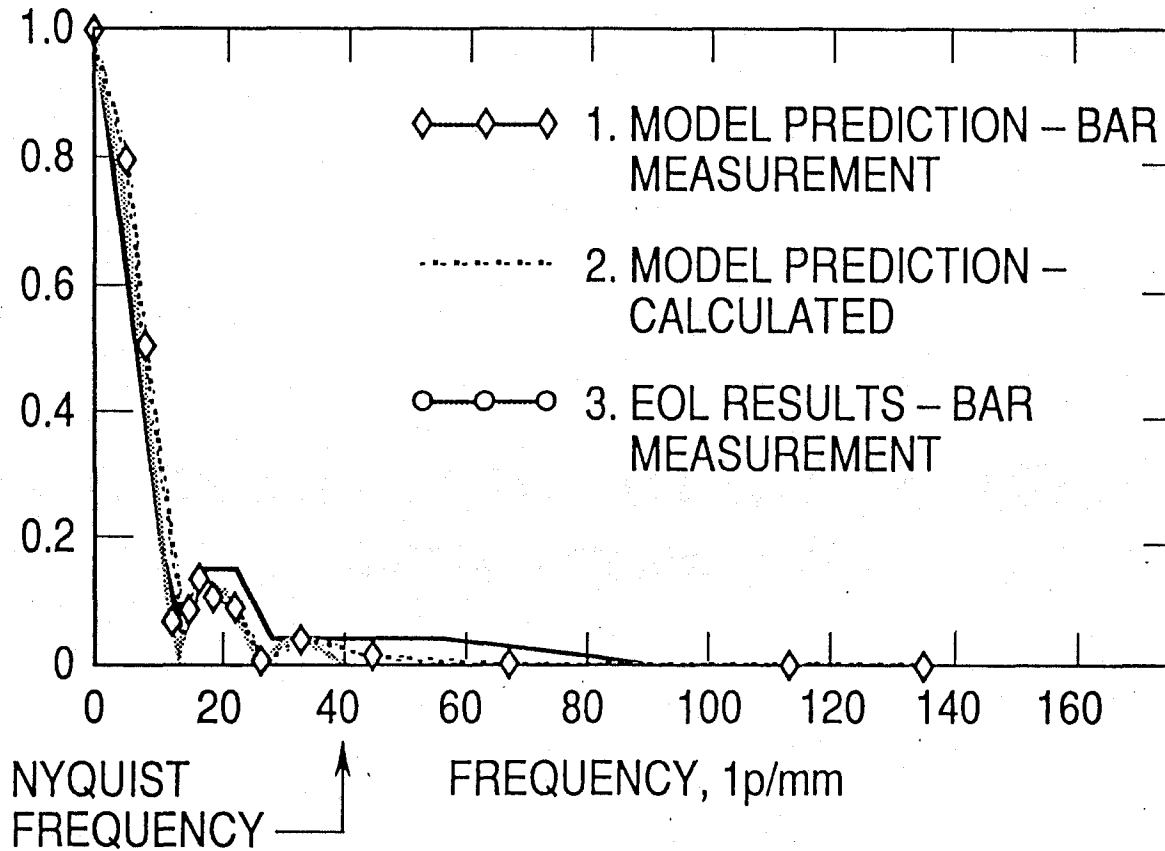
CROSS-SCAN
IN-SCAN

$$\frac{k_y(2)}{k_y(3)} = \frac{\Delta V_y(3)}{\Delta V_y(2)}$$



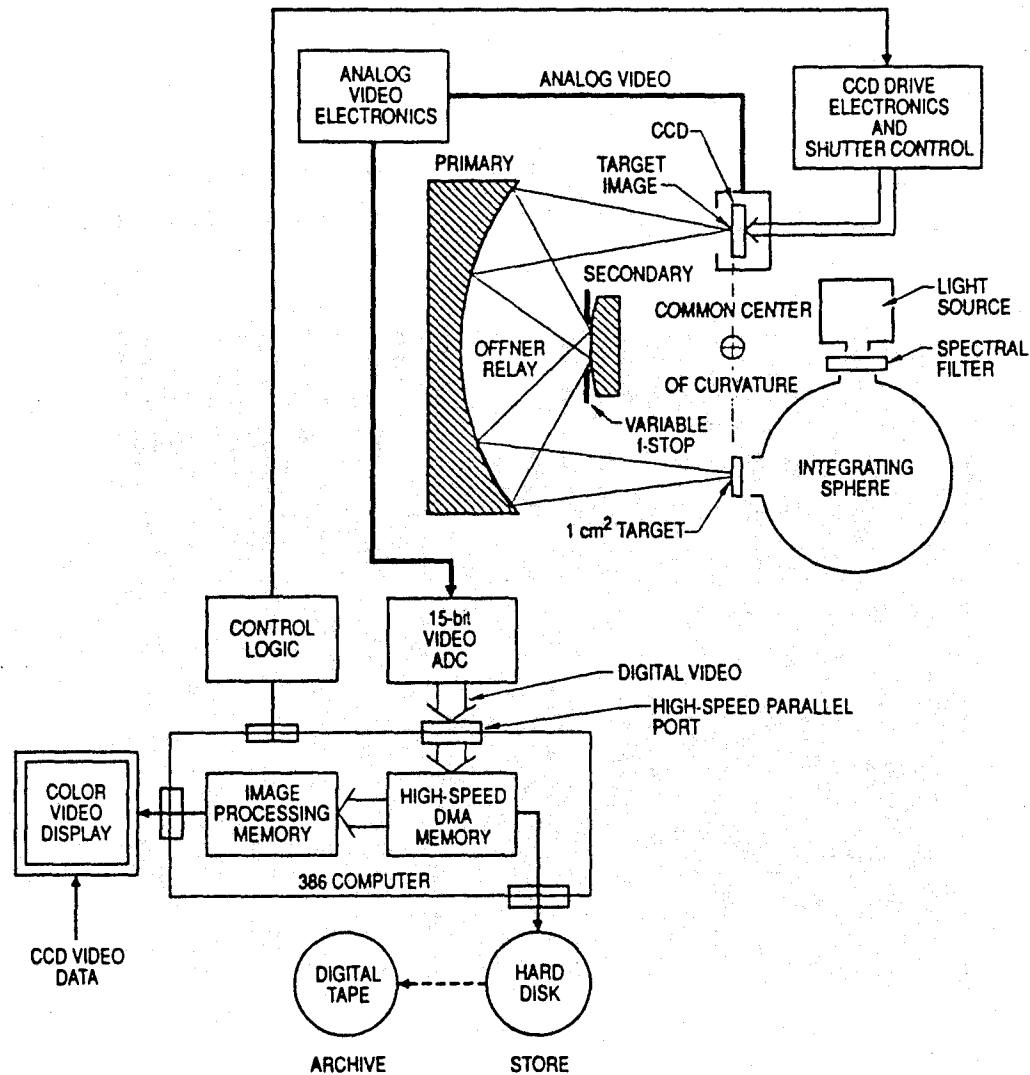
SAME CONFIGURATION AS ABOVE, EXCEPT INDUCED $\Delta V_{\text{MISMATCH}} = 0.00325$ m/sec. ZERO IN $\text{MTF}_{\text{MISMATCH}}$ OCCURS AT BAR PATTERN 3

VELOCITY MISMATCH MTF: ITEK VL-96A CCD



**OFFNER REIMAGER
CCD CHARACTERIZATION SYSTEM**

OFFNER REIMAGING SYSTEM INCLUDING HIGH-RESOLUTION CCD, DIGITAL PROCESSING,
AND IMAGE DISPLAY SUBSYSTEMS



SYSTEM IS USED TO CHARACTERIZE CCD ARRAYS WITH PIXEL PITCH OF $\leq 7\mu\text{M}$

BEAT-PATTERN NEAR NYQUIST

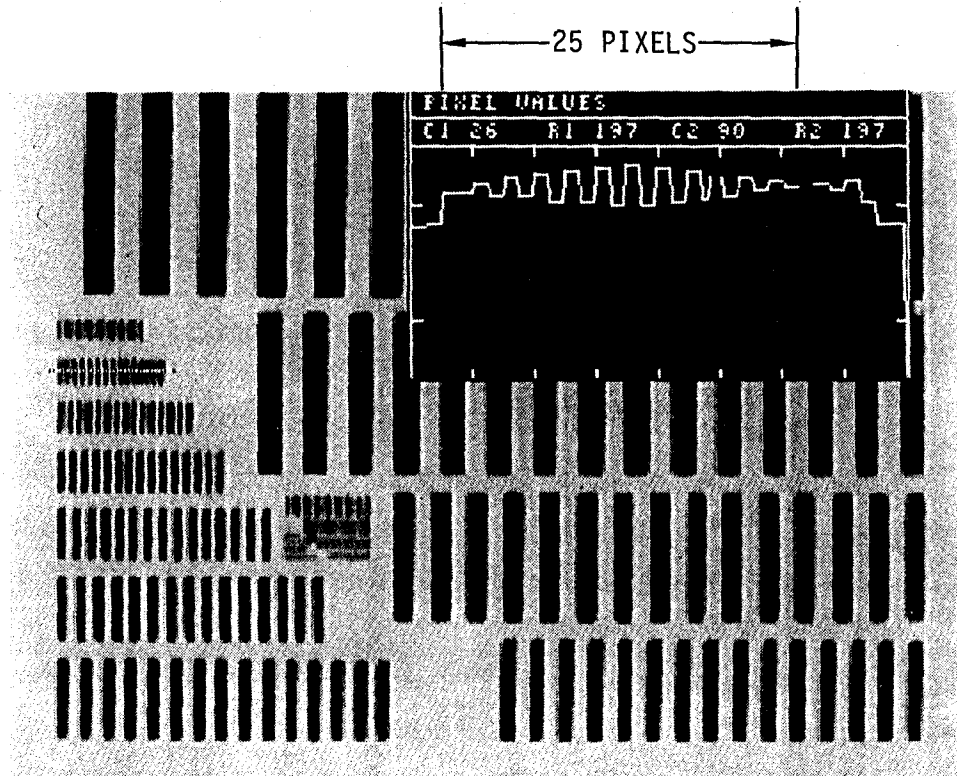


Image profile of the 79.4 lp/mm bar target. The observed beat frequency is precisely that predicted by 1:1 reimaging of that target onto a detector array with a Nyquist frequency of 73.5 lp/mm.

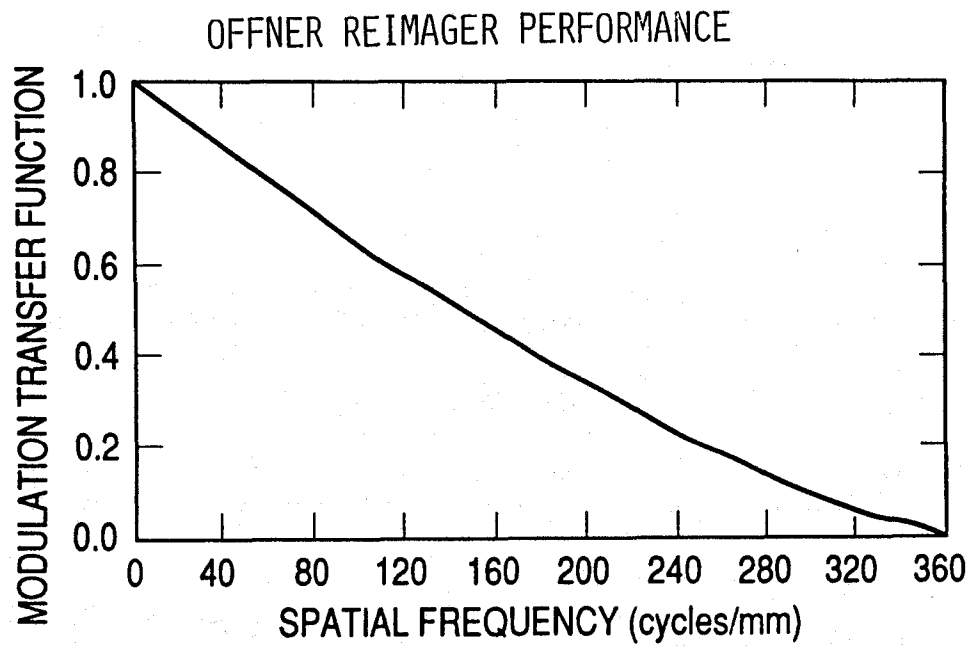
$$F_N = 73.5 \text{ LP/MM}$$

$$F_{\text{BEAT}} = 5.9 \text{ LP/MM}$$

$$F_{\text{BAR}} = 79.4 \text{ LP/MM}$$

→ COVERS $169 \mu\text{M}$

$$\rightarrow \frac{169 \mu\text{M}}{6.8 \mu\text{M}} = 25$$



Modulation Transfer Function (MTF) versus spatial frequency of modified Offner reimager, using Code V, for $f/5$ and 550 nm wavelength.

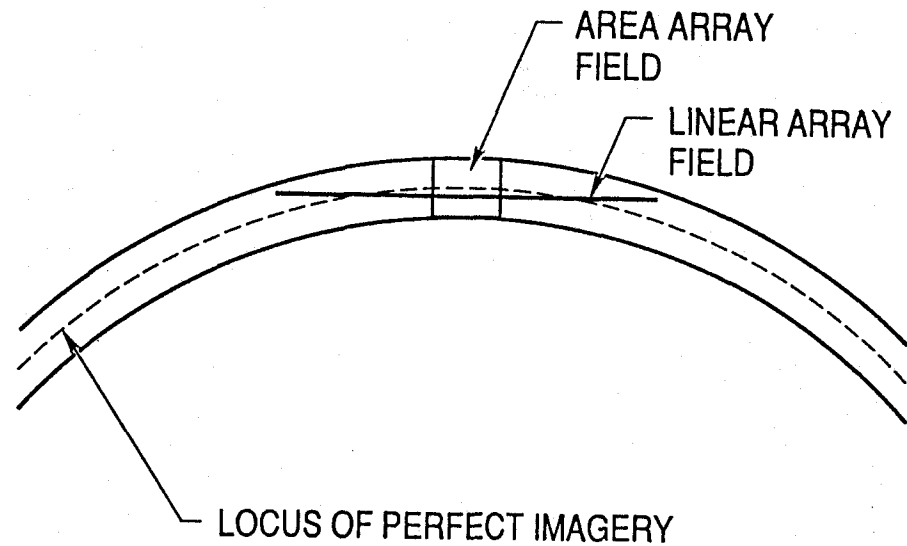
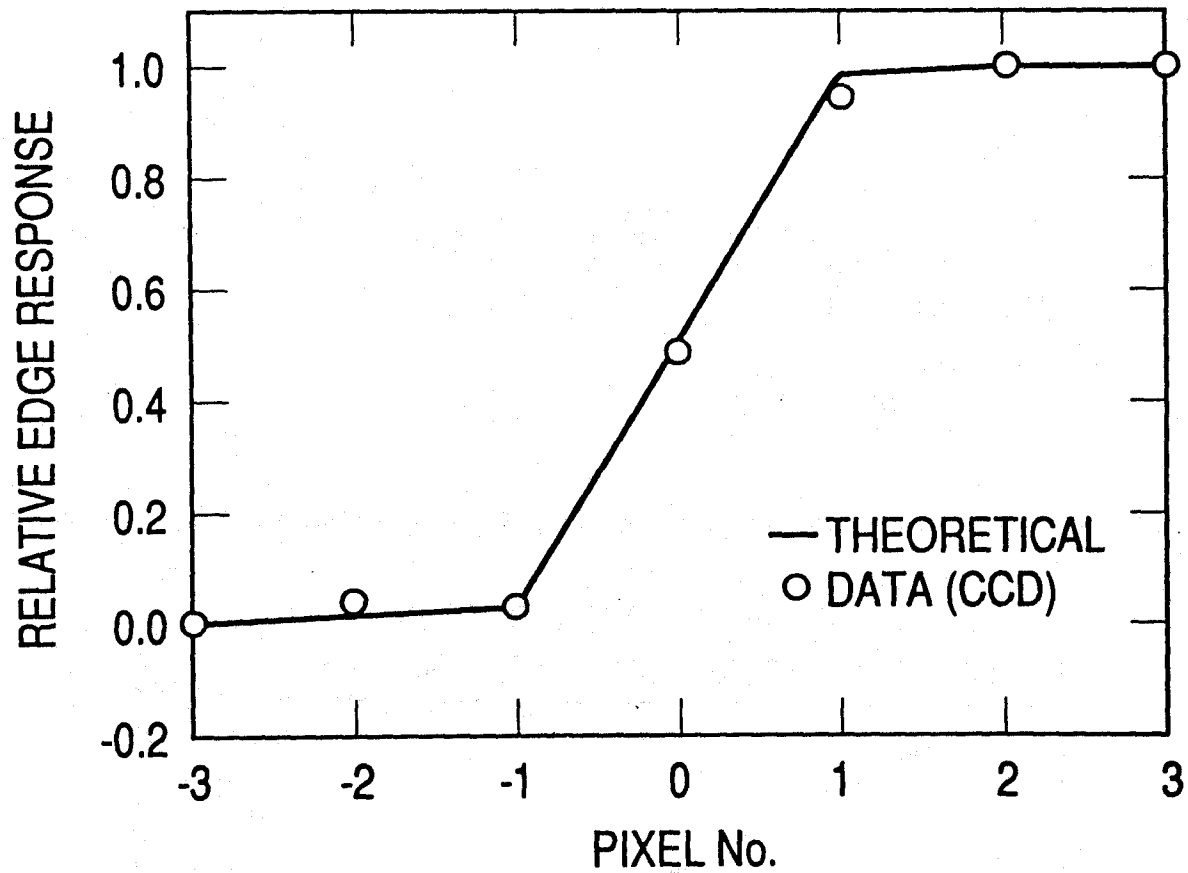


Diagram showing the ability of the "annulus of good imagery" to cover the fields of both area and linear CCD arrays.

EDGE-RESPONSE DATA

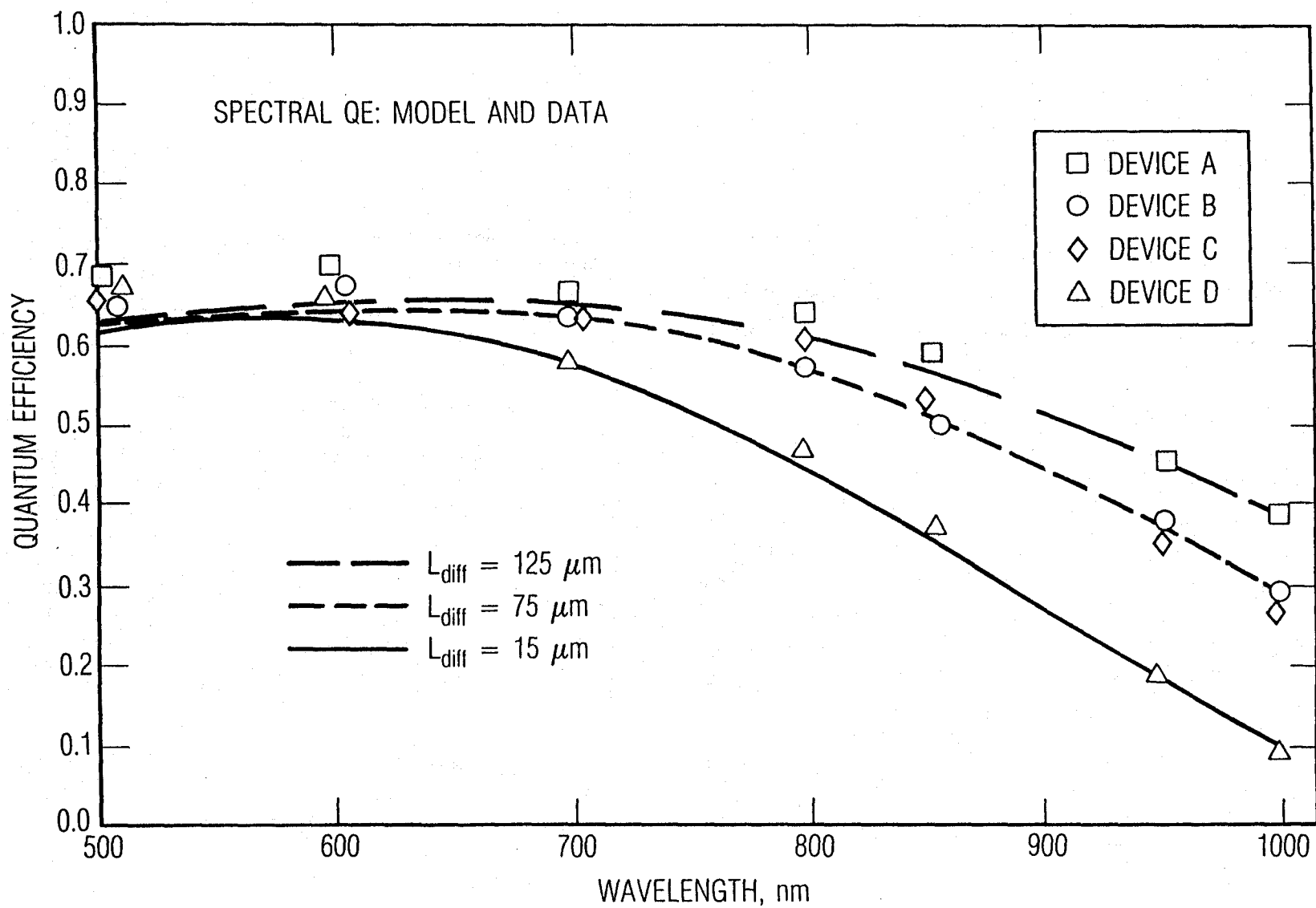


Evidence for diffraction-limited performance of the Offner reimager at f/5 and 550 nm, showing theoretical and experimental responses of a Kodak KAF-1400 CCD to a high-contrast edge.

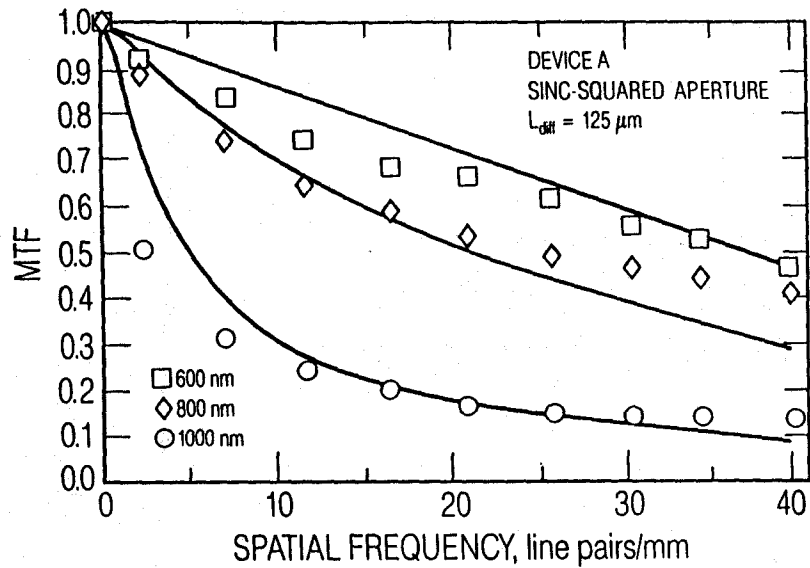
$$ESF(x) = U(x) \otimes PSF_{TOT}(x', y')$$

$$PSF_{TOT}(x, y) = PSF_{OPT} \otimes RECT_{APT}$$

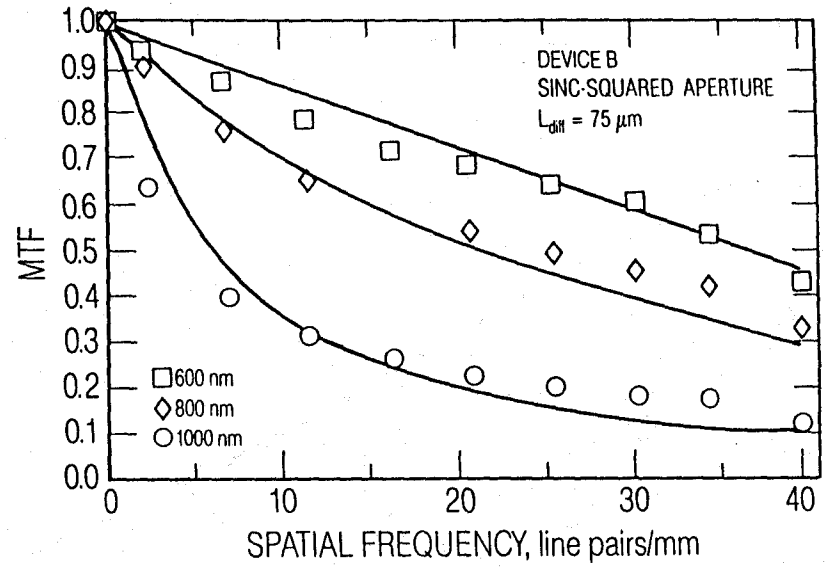
FAIRCHILD LINEAR CCD: SPECTRAL QE DATA



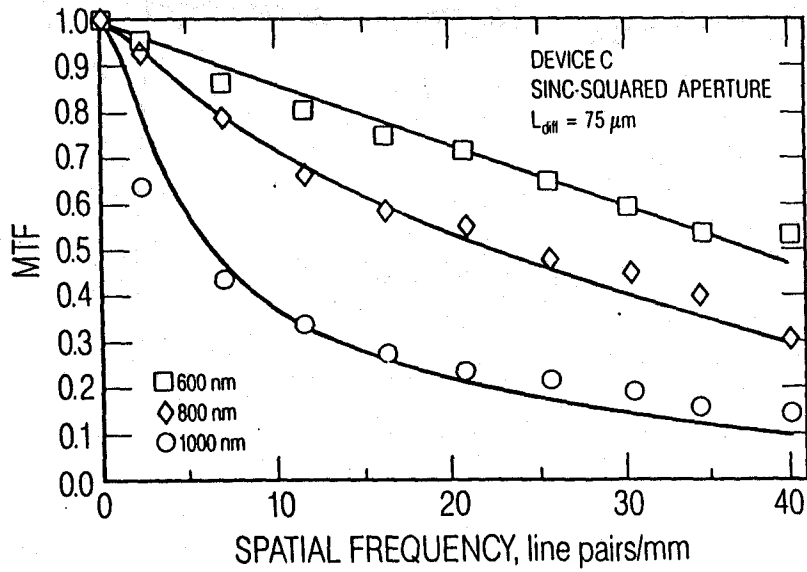
FAIRCHILD LINEAR CCD: SPECTRAL MTF DATA



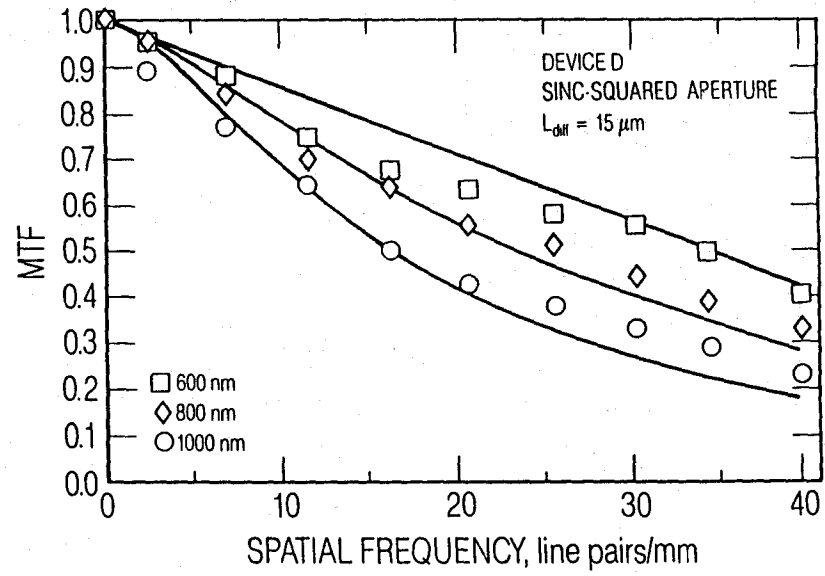
(a)



(b)

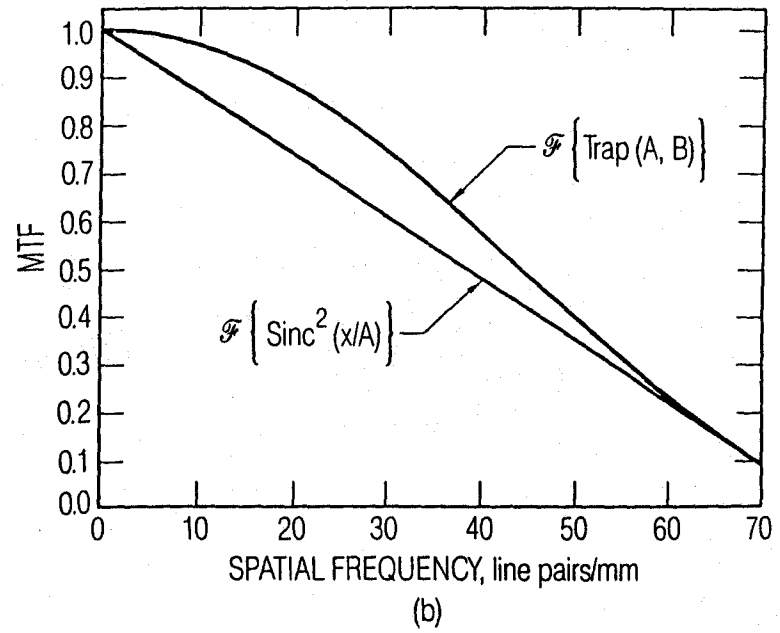
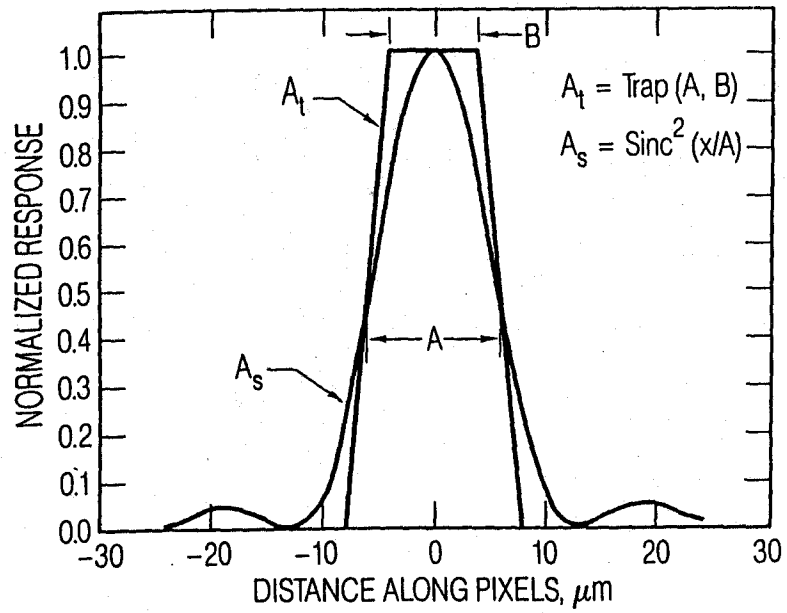


(c)



(d)

TRAPEZOIDAL/SINC-SQUARED PIXEL APERTURES AND MTFs FAIRCHILD LINEAR CCD



FAIRCHILD LINEAR CCD: MTF VERSUS DIFFUSION LENGTH

