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

TERRENCE S. LOMHEIM

THE AEROSPACE CORPORATION
SENSOR SYSTEMS SUBDIVISION
ELECTRO-OPTICAL SYSTEMS DEPARTMENT
EL SEGUNDO, CA 90245-4691

IEEE CHARGE-COUPLED DEVICES WORKSHOP (1991)
UNIVERSITY OF WATERLOO, WATERLOO
ONTARIO, CANADA N2L 3G1
JUNE 9, 1991

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 ⟶ EO SYSTEMS WHICH IMAGE EXTENDED SOURCES (camera systems, document copiers, etc.)

↑

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

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

↑

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

Utility and Interpretability of EO Imaging System Output

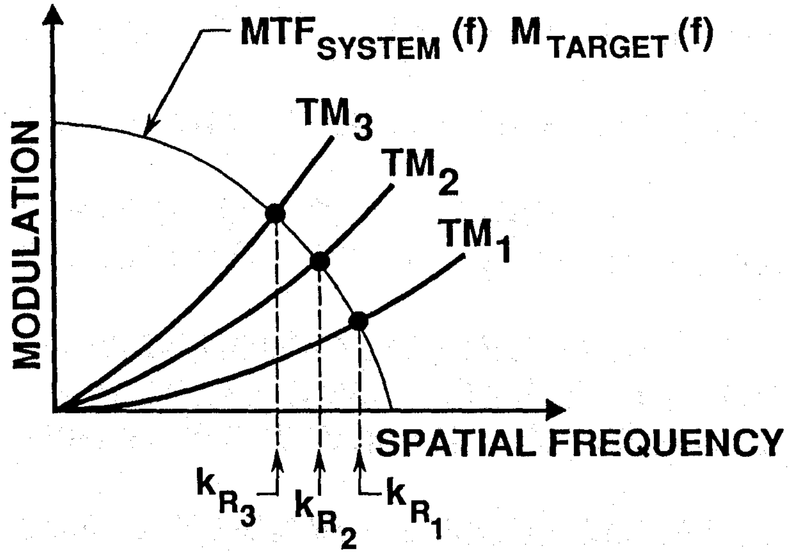
- IMAGE UTILITY AND INTERPRETABILITY DEPENDS, IN A COMPLEX, SUBJECTIVE WAY ON:
  - TARGET CONTRAST
  - EO DETECTION AND DISPLAY SYSTEM MTF

  } 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 ≡ 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 ≃ 2 x PIXEL PITCH FOR A PROPERLY DESIGNED EO IMAGING SYSTEM

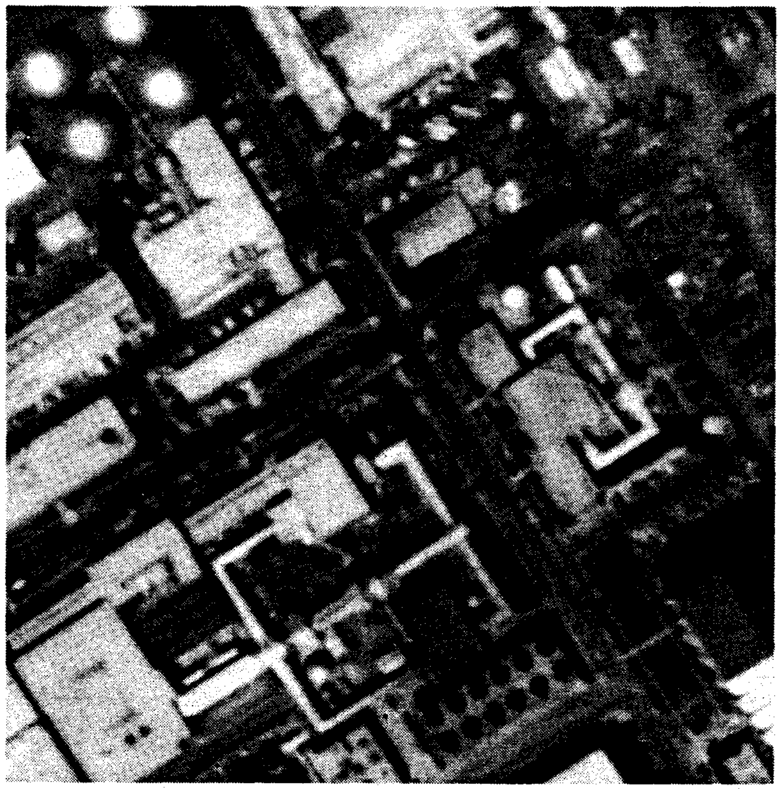
Maximum-Resolved Frequency (f_R) for an EO Imaging System*

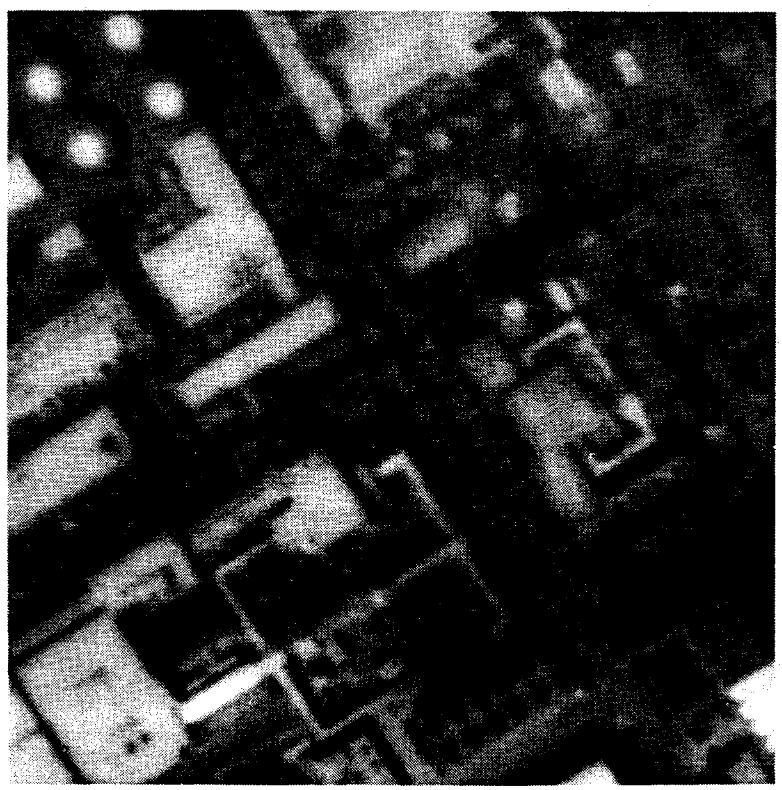


- TM (threshold modulation) $\sim \frac{1}{SNR(f)}$
- SNR$_{min}$ AND HENCE TM CURVES INCREASE MONOTONICALLY WITH SPATIAL FREQUENCY
- k_R = 1/GRD

- 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 → 2D FOURIER TRANSFORM OF INPUT SCENE x 2D SYSTEM MTF → 2D INVERSE FOURIER TRANSFORM → 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*

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

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

- $MTF\ (k_x, k_y) = |OTF\ (K_x, K_y)|$
  - 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 ℓp/mm SINC $\equiv \frac{\text{SIN}\,\pi x}{\pi x}$ AND $x \equiv$ CROSS-SCAN, $y \equiv$ IN-SCAN
A. <u>DETECTOR SPATIAL APERTURE (Trapezoidal)</u>	$MTF_{apt}(k_x, k_y) = MTF_{apt}(k_x, \Delta x, \Delta S_x)\, MTF_{apt}(k_y, \Delta y, \Delta S_y)$ $MTF_{apt}(k, \Delta \ell, \Delta S_\ell) = \text{SINC}(k\Delta\ell)\ \text{SINC}\,[k(\Delta\ell - \Delta S_\ell)]$
B. <u>DETECTOR TEMPORAL APERTURE/SMEAR</u> (J. F. Johnson and R. A. Keller)	$MTF_{int}(k_x, k_y) = \dfrac{\text{SINC}\,[N_{TDI}(k_x\Delta V_x + k_y\Delta V_y)T_{int}]}{\text{SINC}\,[(k_x\Delta V_x + k_y\Delta V_y)T_{int}/N_{ph}]}$ $\times\ \text{SINC}\left[\dfrac{k_x\Delta X + (k_x\Delta V_x + k_y\Delta V_y)T_{int}}{N_{ph}}\right]$
C. <u>CARRIER DIFFUSION</u> (Sieb, IEEE Trans on Electron Devices, <u>Vol ED-21</u>, p 210, 1974)	$MTF_{diff}(k_x, k_y, \lambda) = \dfrac{1 - \left[\dfrac{\exp(-\alpha L_{dep\ell})}{1 + \alpha L}\right]}{1 - \left[\dfrac{\exp(-\alpha L_{depl})}{1 + \alpha L_{diff}}\right]}$ $L = \dfrac{L_{diff}}{\sqrt{1 + 4\pi^2 L_{diff}^2\, k^2}}\ ;\ k^2 = k_x^2 + k_y^2;\ L_{diff} = \sqrt{D\tau}$
D. <u>OPTICAL DIFFRACTION</u> (E. L. O'Neill, JOSA, Vol 46, p 285, 1956)	$MTF_{opt}(k_x, k_y, \lambda)$ and $k = \sqrt{k_x^2 + k_y^2}$ (use O'Neill formula if optics is diffraction limited)
E. <u>OPTICAL DEGRADATION</u> (D. Nicholson, Proc of SPIE Vol 54, p 163, 1975)	$MTF_{od}(k_x, k_y, \lambda)$ and $k = \sqrt{k_x^2 + k_y^2}$ (use Nicholson equations)

COMPOSITE SYSTEM MTF:

F. $MTF_{total}(k_x, k_y) = MTF_{apt}(k_x, k_y)\, MTF_{int}(k_x, k_y)\, MTF_{diff}(k_x, k_y)\, MTF_{opt}(k_x, k_y)\, MTF_{od}(k_x, k_y)$

TRUE AT A SINGLE λ

$\Delta X, \Delta Y$ = PIXEL WIDTH (x, y)

$\Delta S_x, \Delta S_y$ = PIXEL FLAT-RESPONSE WIDTH (x, y)

N_{TDI} = # TDI STAGES

ΔV_x = VELOCITY ERROR: X-DIRECTION

ΔV_y = VELOCITY ERROR: Y-DIRECTION

T_{int} = INTEGRATION TIME

N_{ph} = # CLOCK PHASES/PIXEL

α = ABSORPTION COEFFICIENT OF SILICON AT λ

$L_{dep\ell}$ = CCD DEPLETION WIDTH

L_{diff} = DIFFUSION LENGTH

ONE SAMPLE/DWELL ASSUMED IN THE IN-SCAN DIRECTION

2D MTF Components: Temporal Integration and TDI Velocity Mismatch

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

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

- If $\Delta V_y = O$, NO CROSS-SCAN DRIFT-VELOCITY AND $k_y = O$ THEN <u>IN-SCAN MTF IS:</u>

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

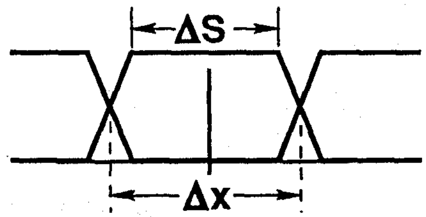
- If $f_x = O$, <u>CROSS-SCAN MTF</u> IS:

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

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

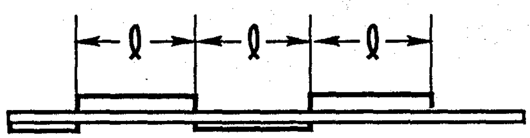
2D MTF Components: Detector Aperture

TRAPEZOIDAL APERTURE

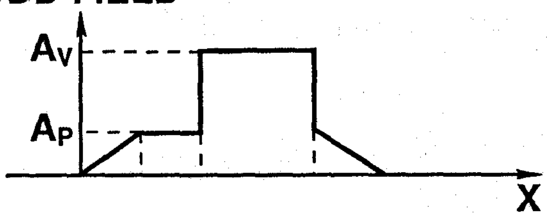


MTF = SINC (kΔx) SINC [k (Δx - ΔS)]

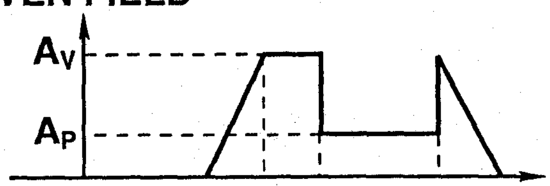
PATTERNED-ELECTRODE APERTURE RESPONSE (after Hosack, IEEE Trans on Elect Device, Vol Ed-28, p 53, 1981) ODD-FIELD/EVEN-FIELD VIRTUAL PHASE CCD



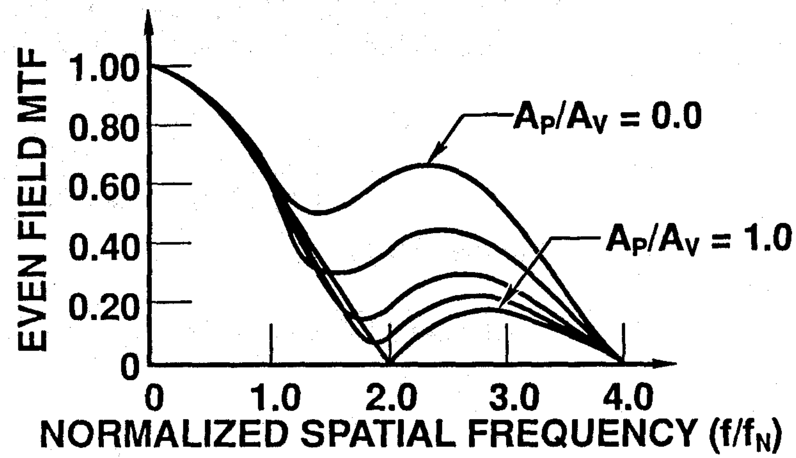
CELL N RESPONSE
ODD FIELD

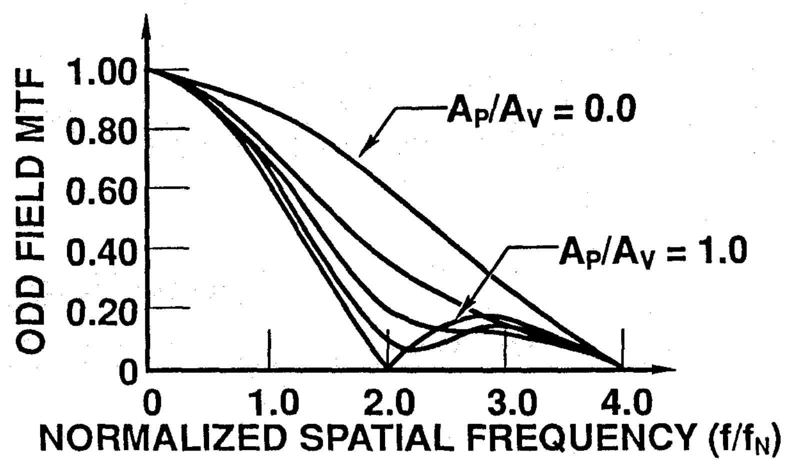


CELL N RESPONSE
EVEN FIELD



$A_P/A_V = 1.0$
GIVES
TRAPEZOIDAL
APERTURE
RESPONSE





2D MTF Components: Carrier Diffusion

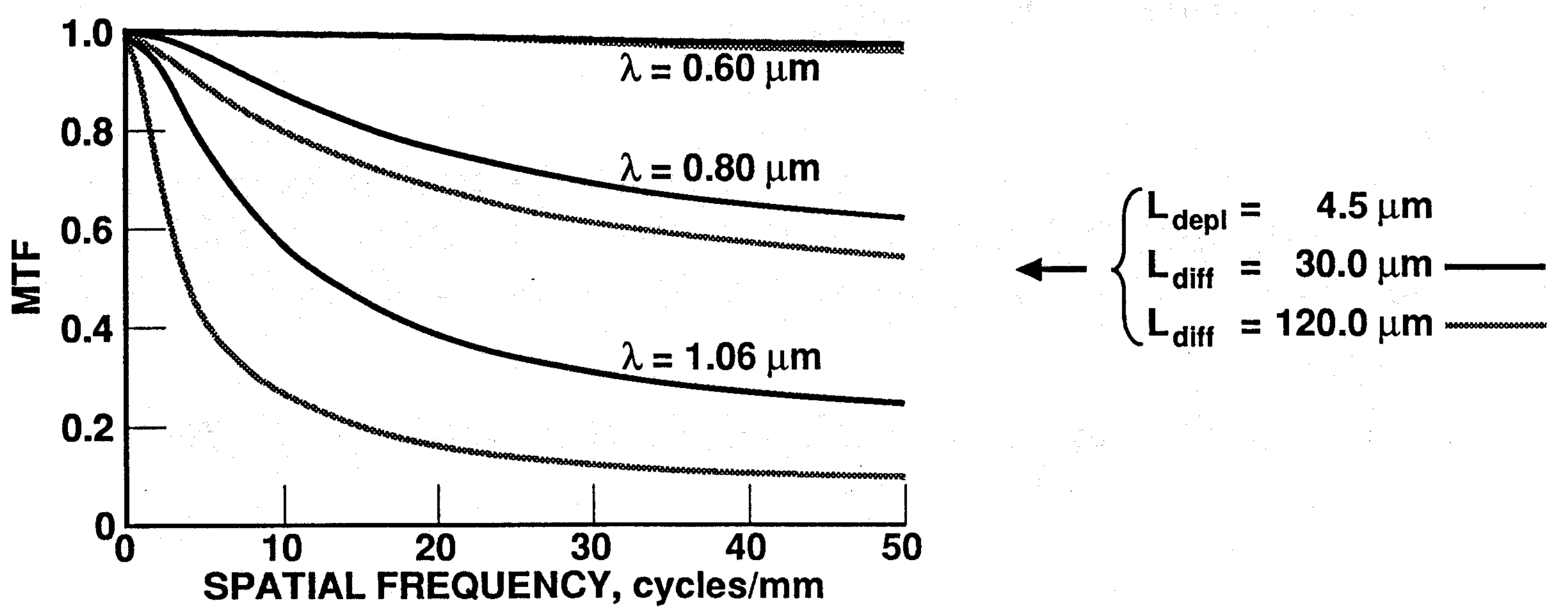
- SIEB MODEL TREATS CARRIER-DIFFUSION IN 2D USING DIFFUSION EQUATION WITH APPROPRIATE BOUNDARY CONDITIONS AND SINUSOIDAL GENERATION TERM

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

$$\text{AND} \quad k^2 = k_x^2 + k_y^2$$

<u>NOTE:</u> 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, <u>VOL ED-19</u>, 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:

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

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

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

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

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

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

Spatial Sampling and Aliasing

- SPATIALLY-MODULATED INFORMATION ABOVE THE SAMPLING FREQUENCY, fs, (k_S = 1/ pixel pitch) NECESSARILY APPEARS IN THE $0 \rightarrow k_N$ REGION (k_N = Nyquist frequency)

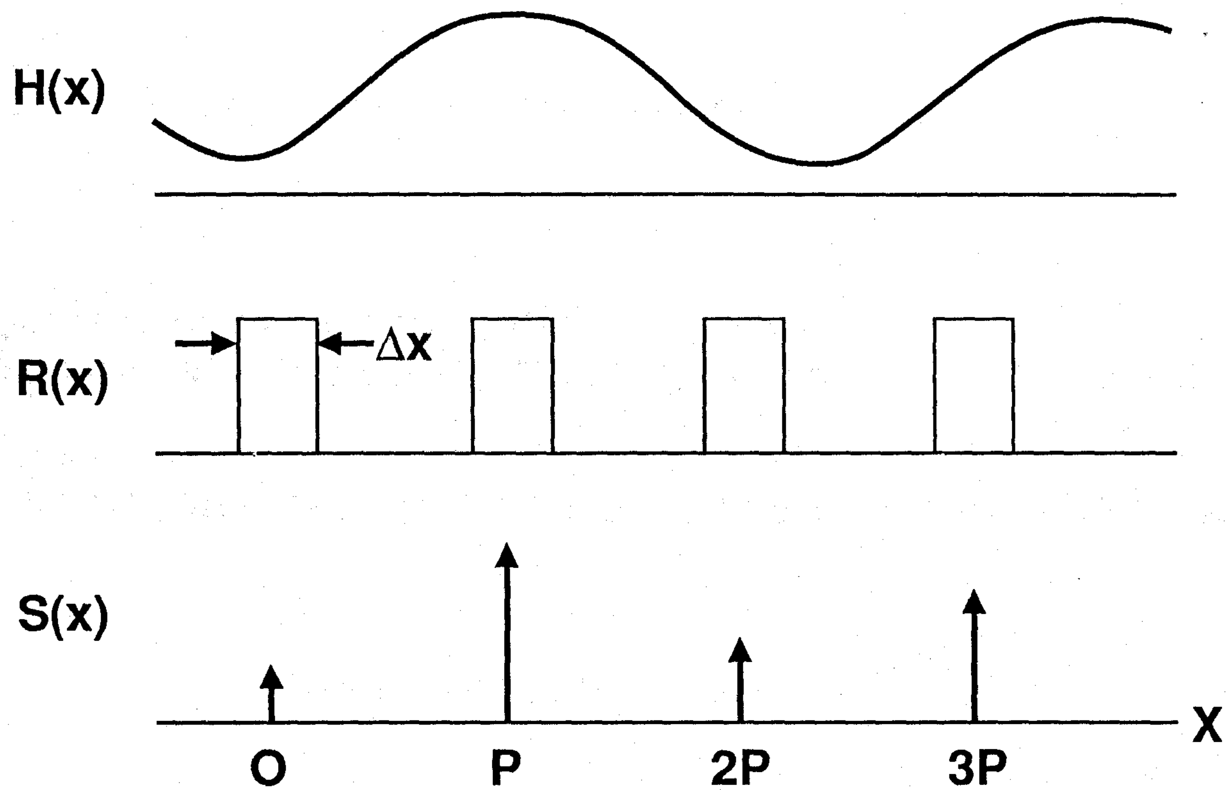
- ALIASING BY A FREQUENCY $k > k_N$ OCCURS IN THE BAND $0 < k' < k_N$. k' IS GIVEN BY*

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

- IF $k'_N = 10\ell$ p/mm, YOU MIGHT GET CONTRIBUTIONS (aliased) FROM $2\, k_N \pm 10$, $4\, k_N \pm 10 \ldots \ell$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



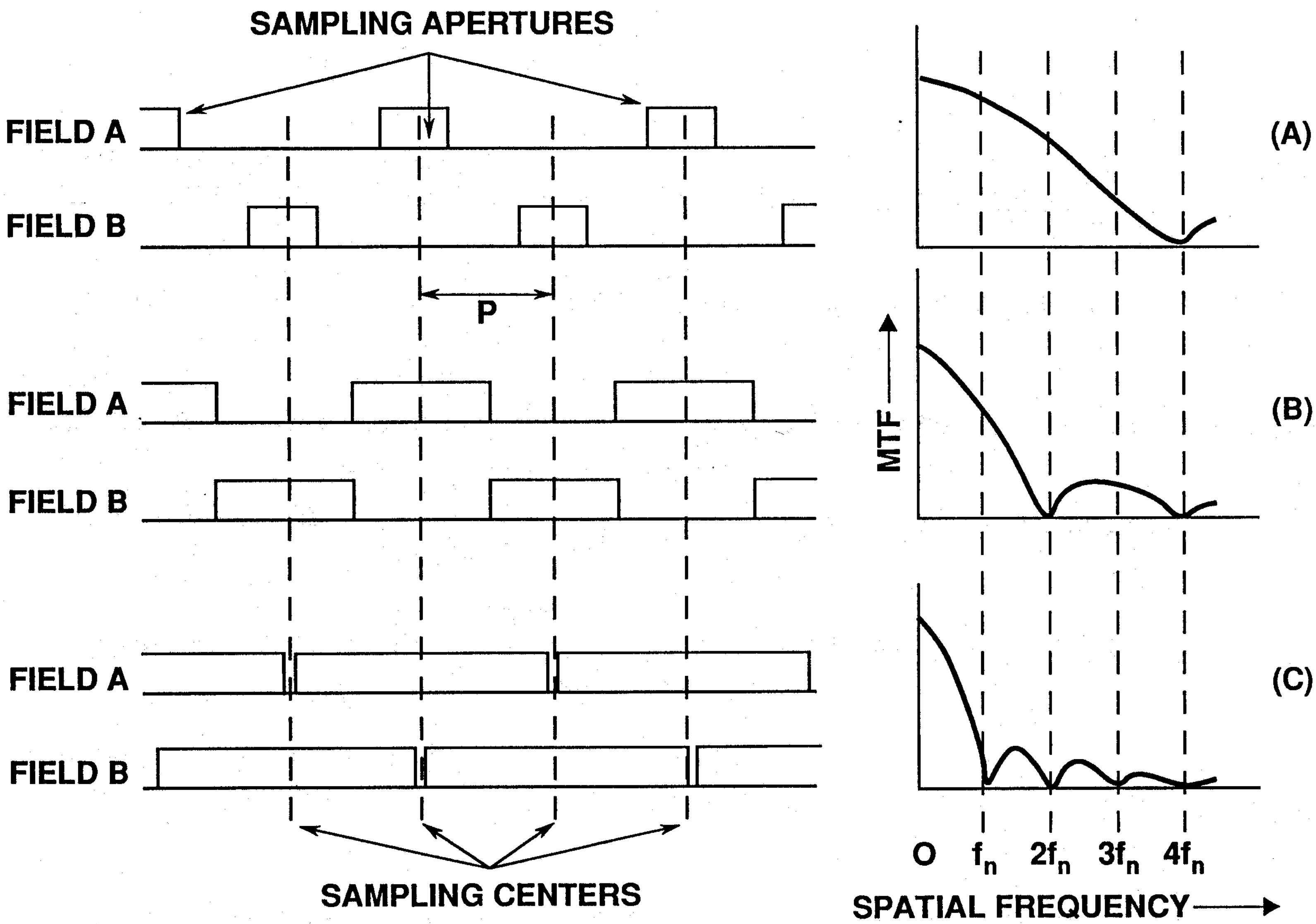
H(x) = INPUT IRRADIANCE

R(x) = APERTURE FUNCTION

S(x) = OUTPUT SIGNAL

MTF ≡ FOURIER – TRANSFORM OF APERTURE FUNCTION

$$\mathrm{MTF} = \frac{\sin \dfrac{\Pi \Delta x}{2P} \cdot \dfrac{k}{k_n}}{\dfrac{\Pi \Delta x}{2P} \cdot \dfrac{k}{k}} \quad , \quad k_n \equiv \frac{1}{2P}$$

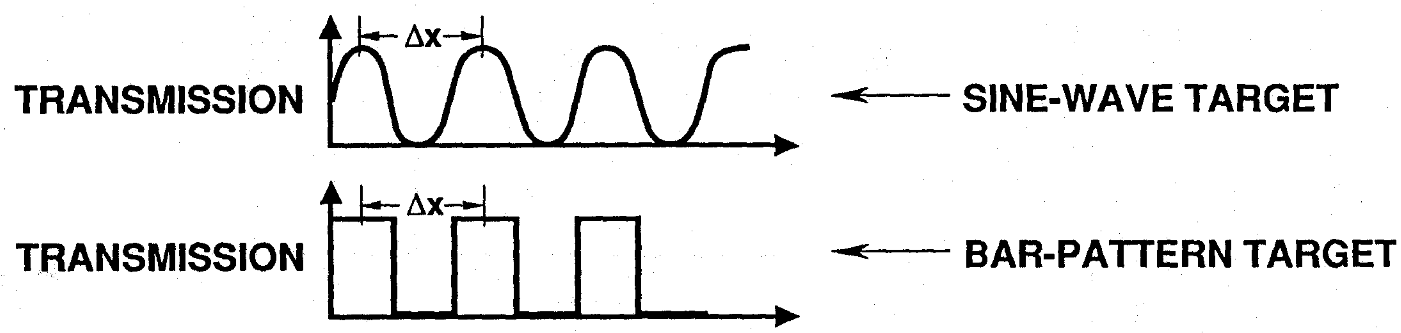

SAMPLING APERTURES
FIELD A
FIELD B
P
FIELD A
FIELD B
FIELD A
FIELD B
SAMPLING CENTERS
MTF
(A)
(B)
(C)
O
f_n
$2f_n$
$3f_n$
$4f_n$
SPATIAL FREQUENCY

(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

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

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

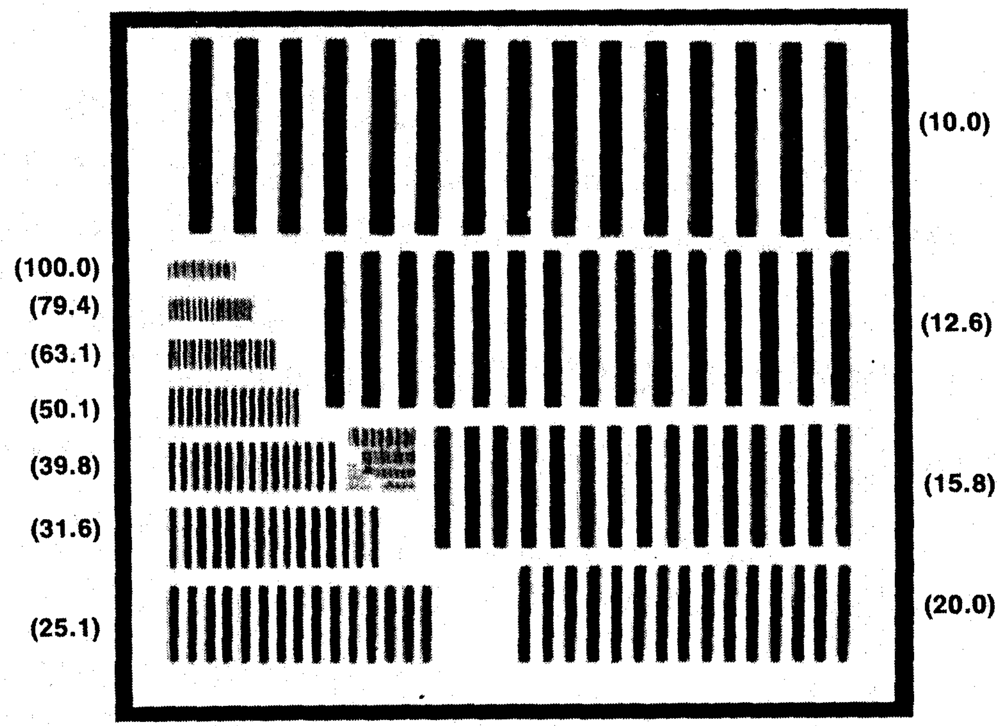
$$MTF\ (k) = \frac{\pi}{4}\left[CTF\ (k) + \frac{CTF\ (3k)}{3} - \frac{CTF\ (5k)}{5} + \frac{CTF\ (7k)}{7} + \ldots\right]$$

* 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

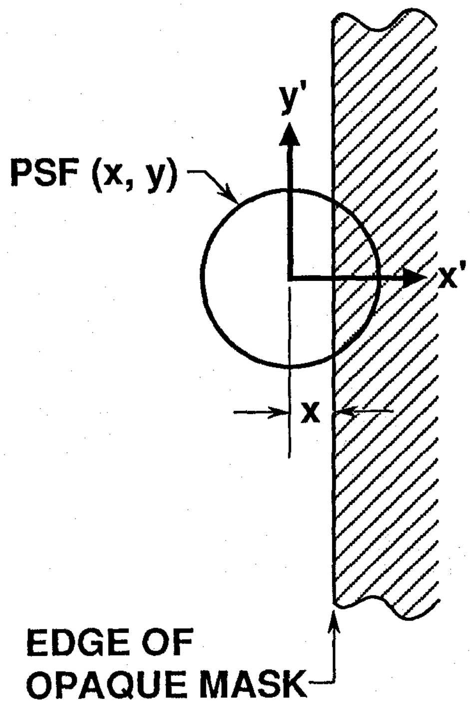
BAR-PATTERN SEQUENCE USED FOR CCD MTF CHARACTERIZATION



LABELED IN LINE PAIRS/MM

OPTICAL MTF MEASUREMENT DESCRIPTION

Relationship Between Point, Edge, Line-Spread Function*



EDGE-SPREAD FUNCTION

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

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

UNIT-STEP FUNCTION (opaque mask edge)

2D CONVOLUTION

LINE-SPREAD FUNCTION

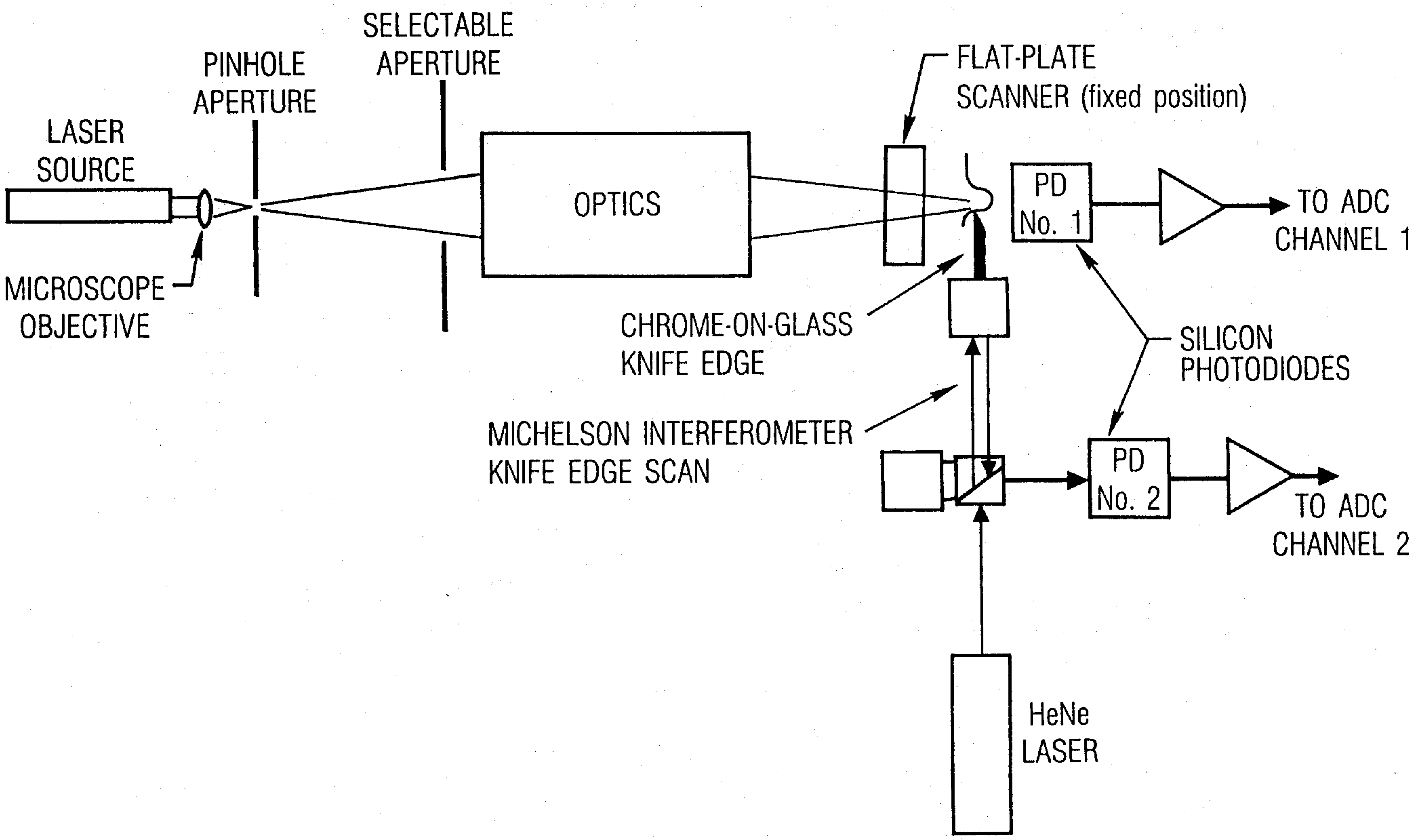
$$LSF(x) = \frac{d\,[ESF(x)]}{dx}$$

MTF IN X-DIRECTION

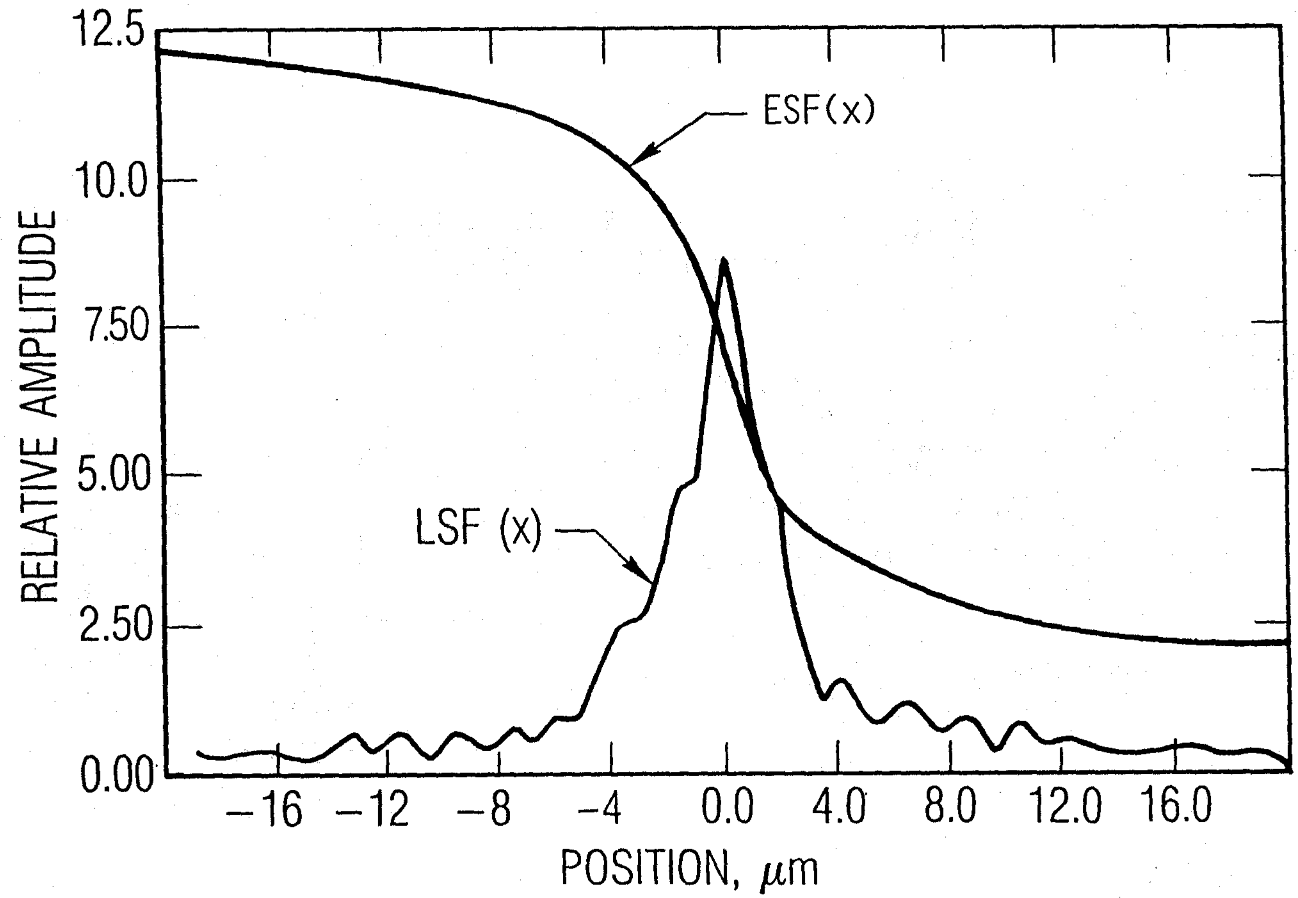
$$MTF(k_x) = FT\,\{LSF(x)\}$$

* 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

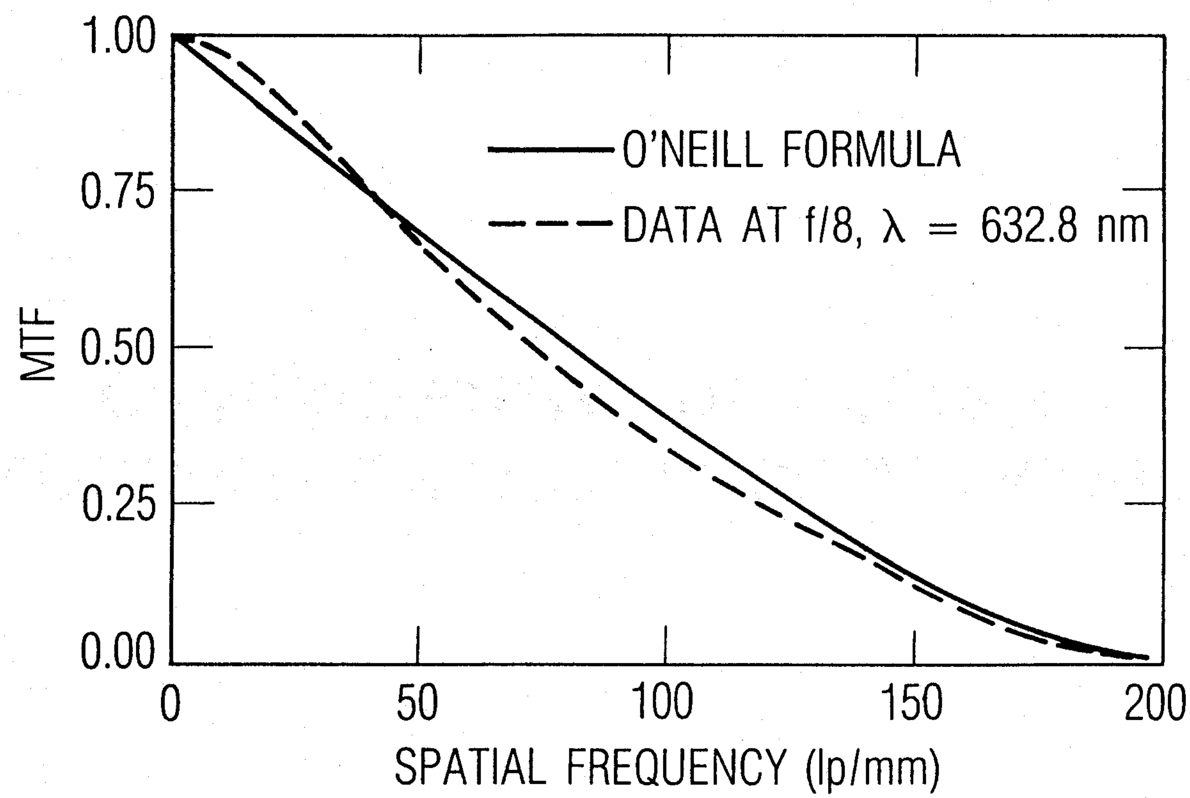


KNIFE-EDGE SCAN OF FOCUSED SPOT
OPTICAL MTF CHARACTERIZATION



MEASURED AND THEORETICAL MTFs FOR OPTICAL SYSTEM

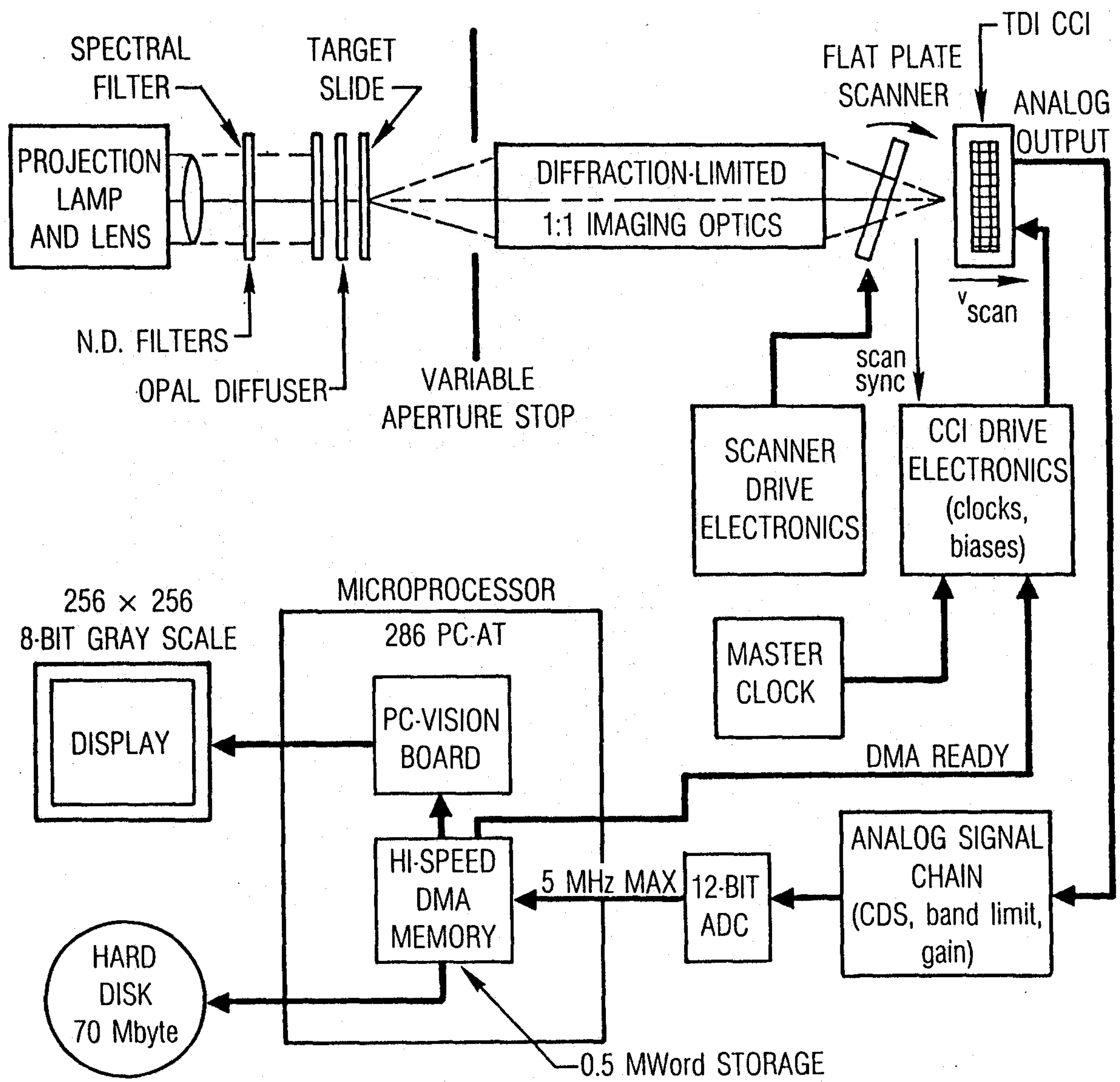
F#/8 AND λ = 632.8 NM



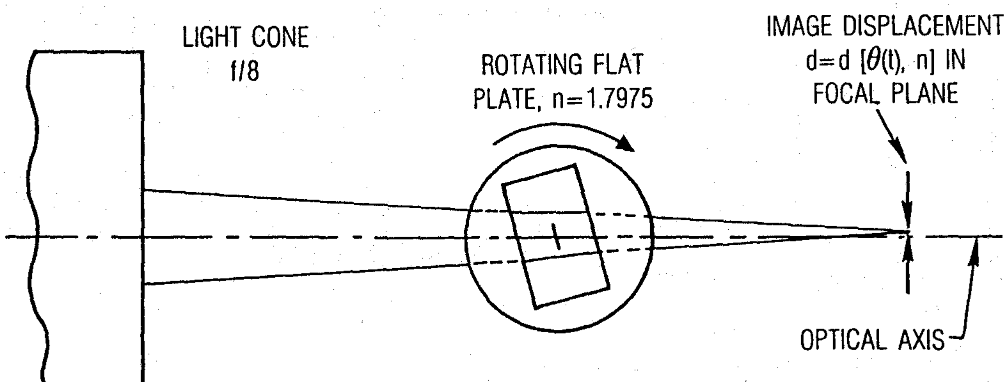
DESCRIPTION OF TDI-CCD SCANNER CHARACTERIZATION SYSTEM*

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

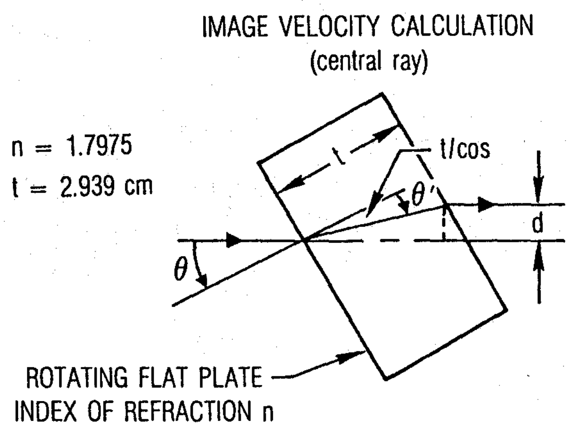
ELECTRO-OPTICAL SCANNING IMAGING SYSTEM USED FOR CHARACTERIZING TDI CCIs



ROTATING FLAT-PLATE SCANNER



(a) Side-view of the rotational flat-plate scanner, including the exit aperture of the optics and the focal plane location.



$$d = \left(\frac{t}{\cos\theta'}\right)\sin(\theta-\theta')$$

$$d \simeq t\,(\theta-\theta'),\ \theta-\theta' \leq 13^\circ$$

$$\theta' = \theta/n, \text{ SNELL'S LAW}$$

$$d = t\,\theta\left(\frac{n-1}{n}\right)$$

$$\boxed{v = \dot{d} = t\left(\frac{n-1}{n}\right)\dot{\theta}}$$

(b) Ray diagram of flat-plate scanner illustrating its principle of operation, including the focal plane image velocity equation.

PHASE-LOCKED LOOP ROTATION CONTROL

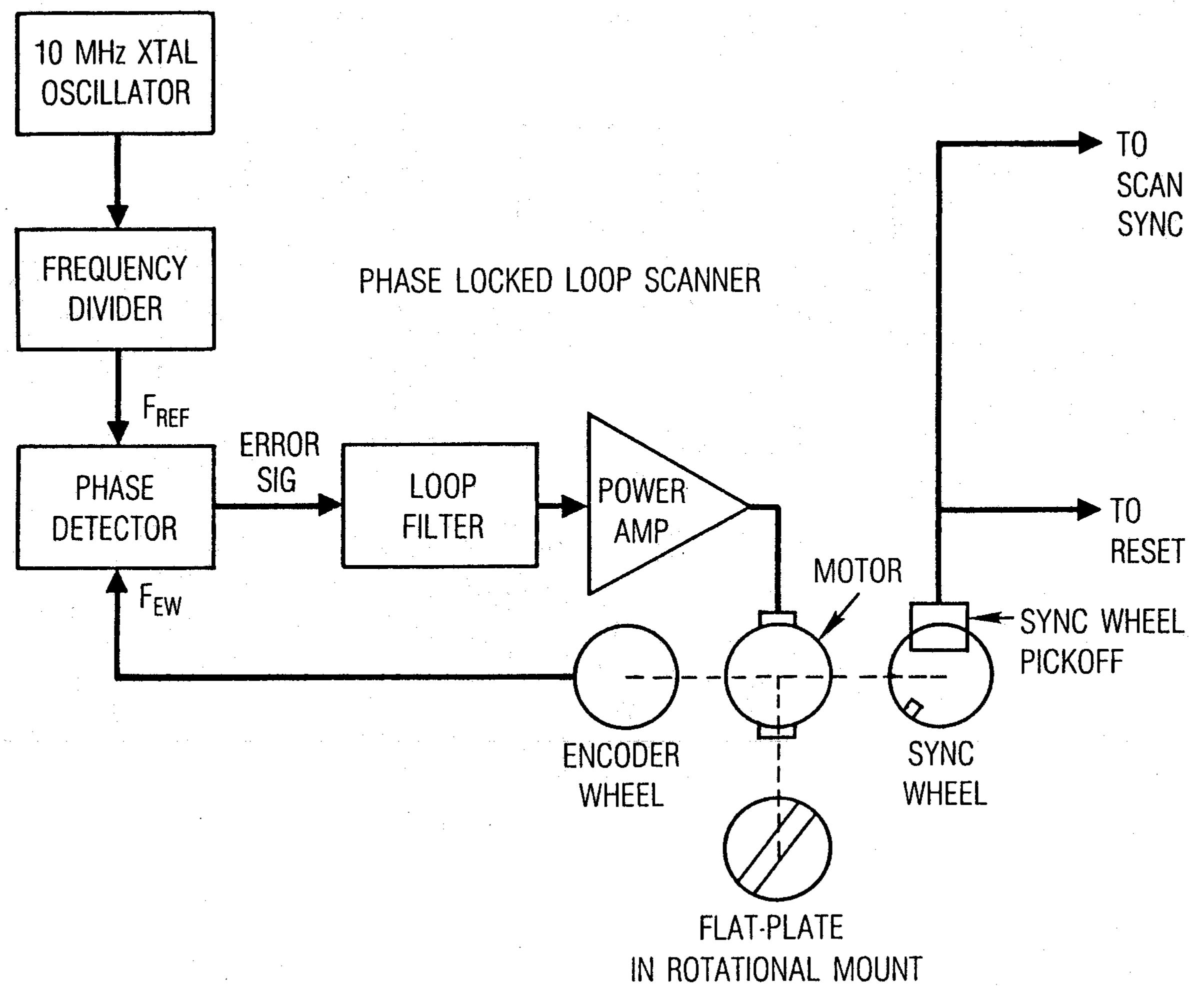
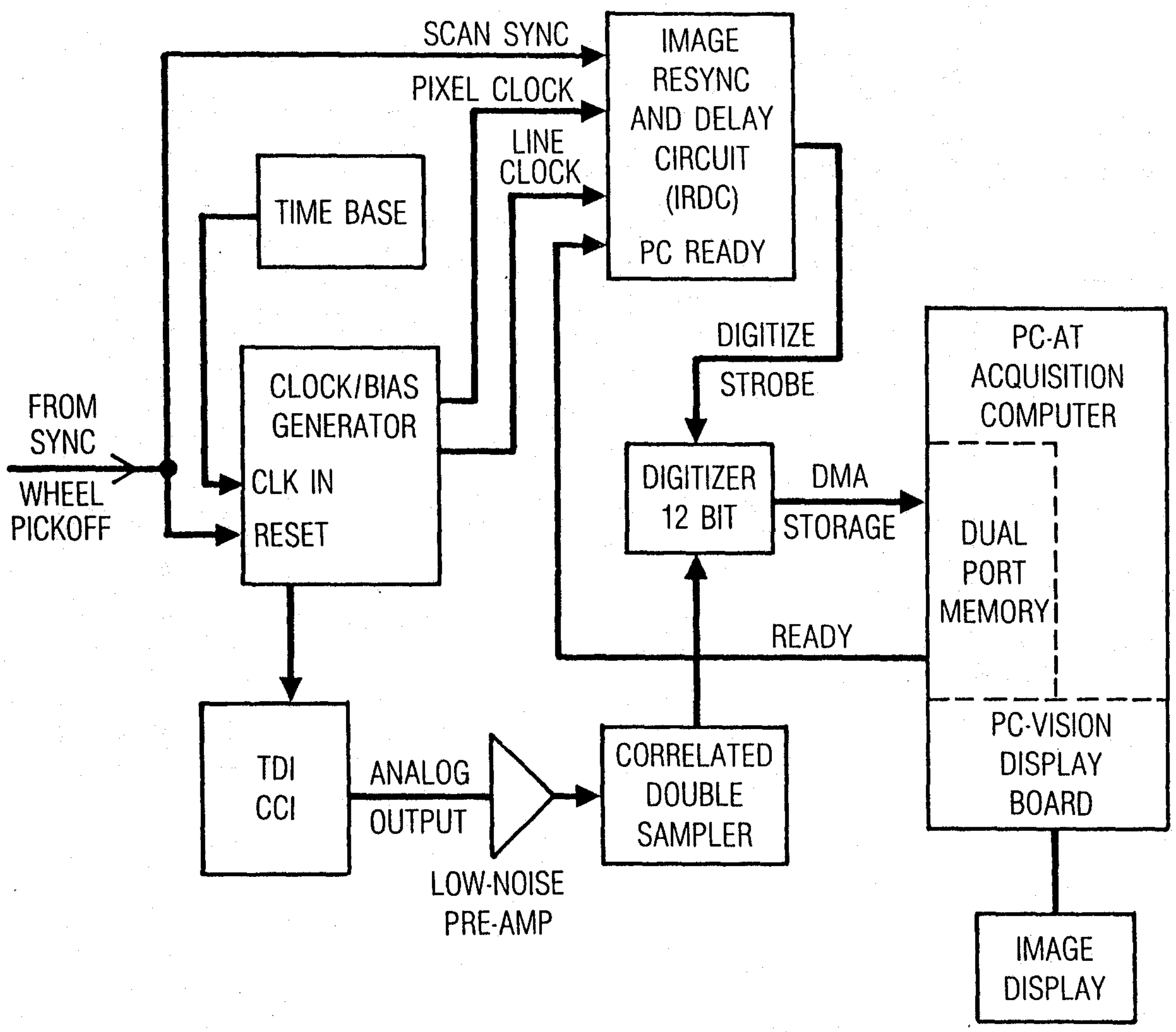
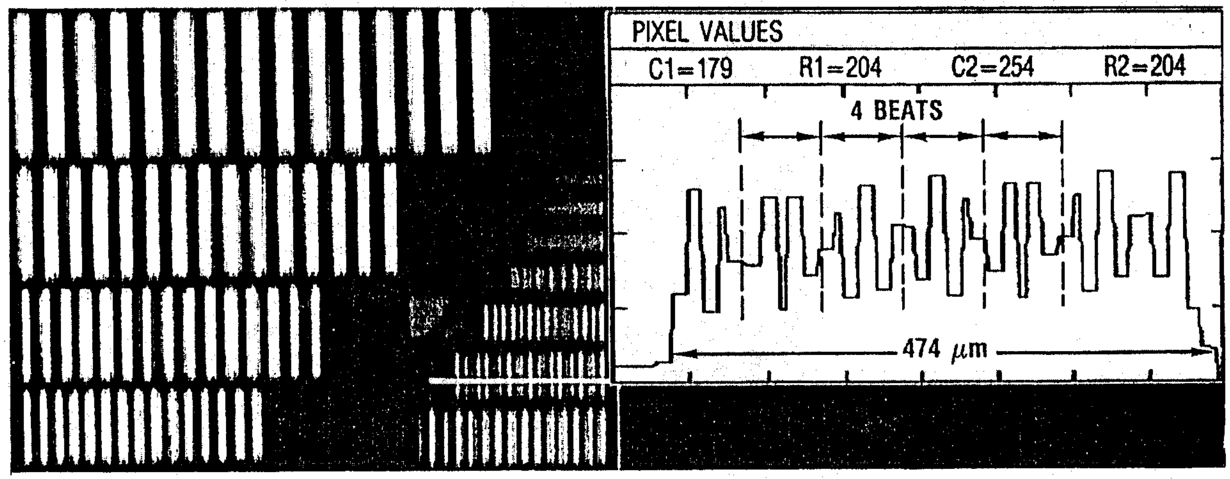


IMAGE-LINE SYNCHRONIZATION ELECTRONICS

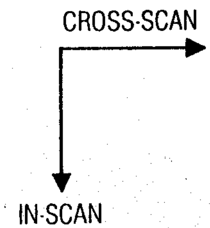


Cross-Scan Beat Patterns

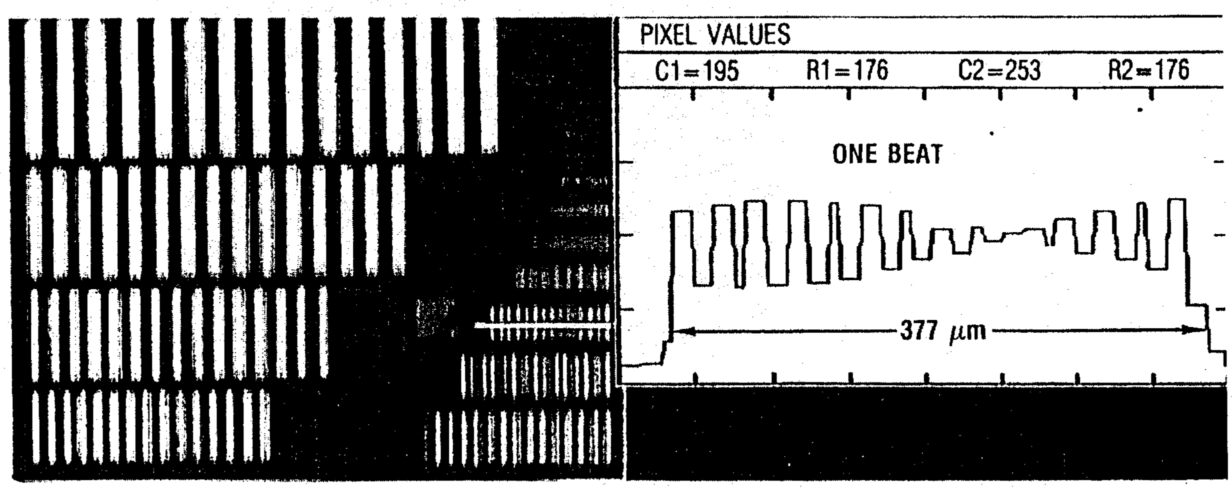


f_N = 38.46 lp/mm
PATTERN 6 = 31.63 lp/mm

f_{BEAT} = 6.83 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_{BEAT} = 1.36 lp/mm ONE BEAT = 28.5 PIXELS

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

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

$$\downarrow$$

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

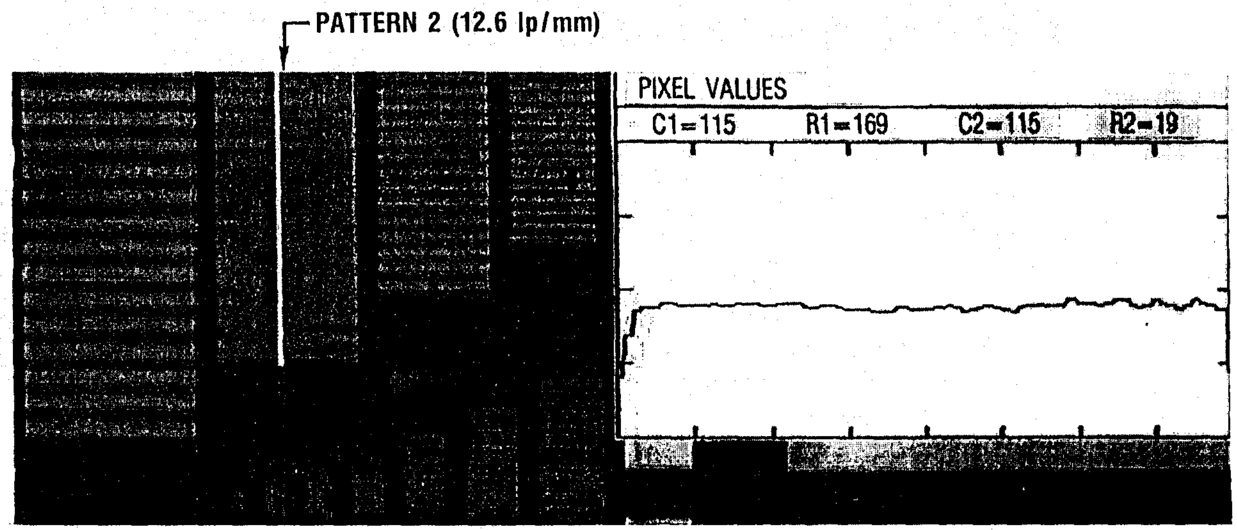
$$\downarrow$$

$$\text{MTF} = 0$$

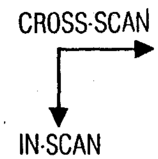
FOR

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

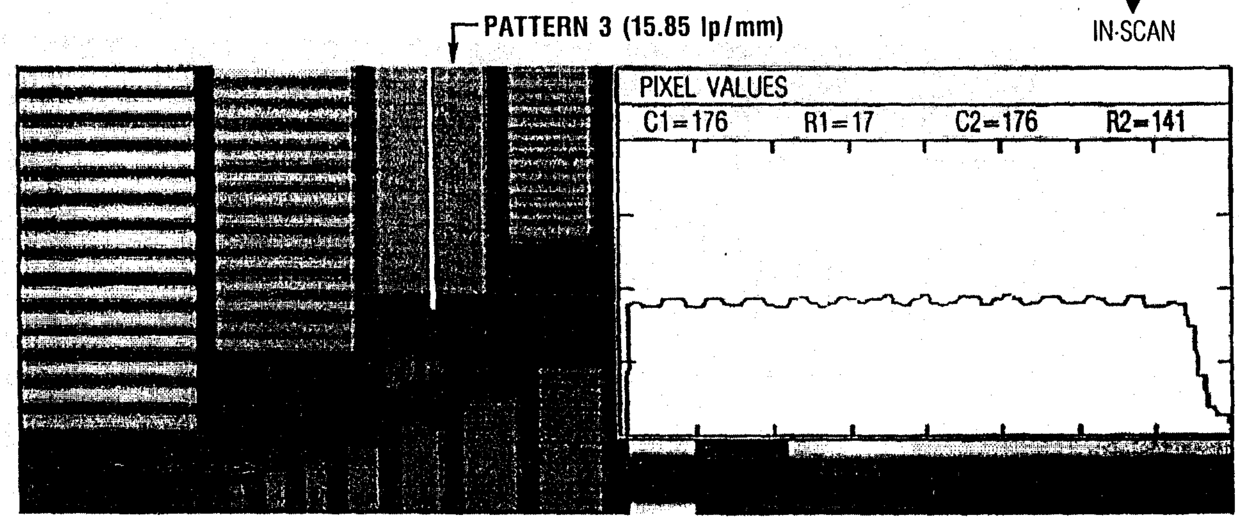
$m = 1$ (for this case)



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

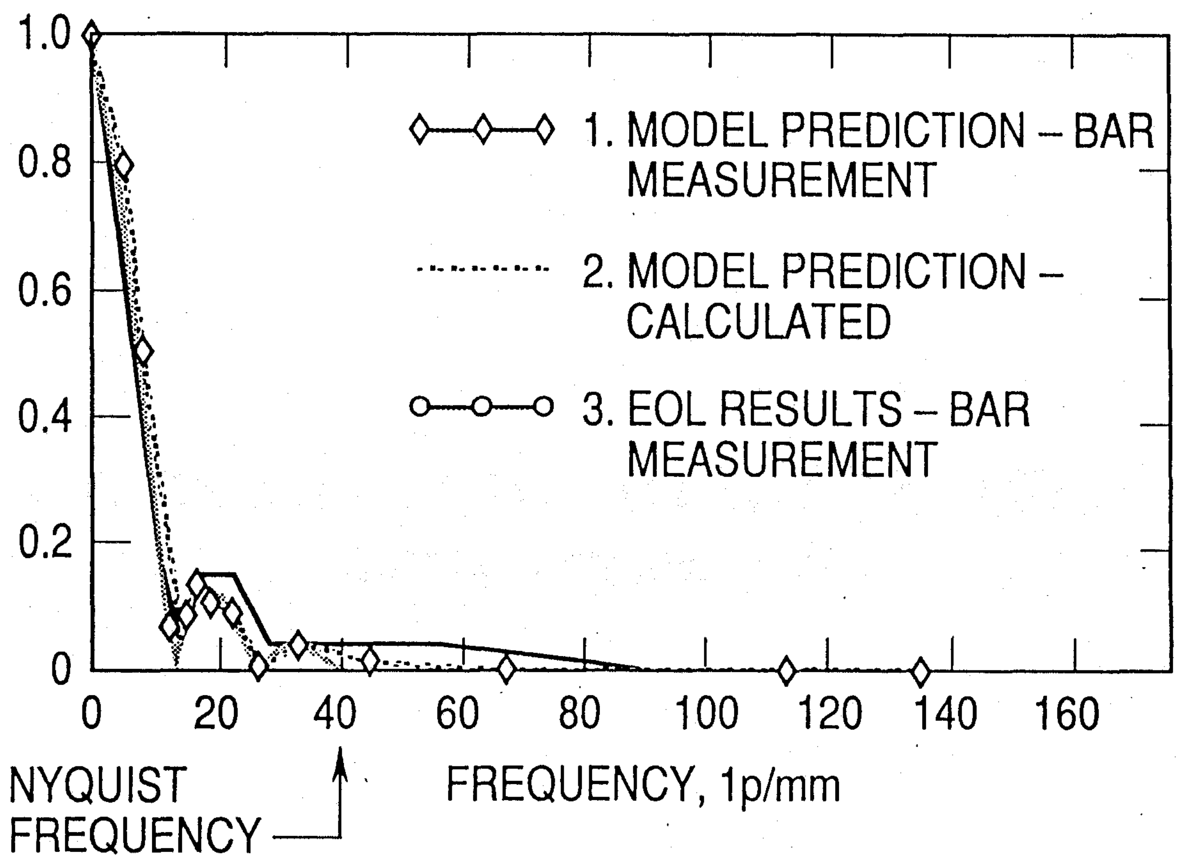


$$\frac{k_y^{(2)}}{k_y^{(3)}} = \frac{\Delta V_y^{(3)}}{\Delta V_y^{(2)}}$$



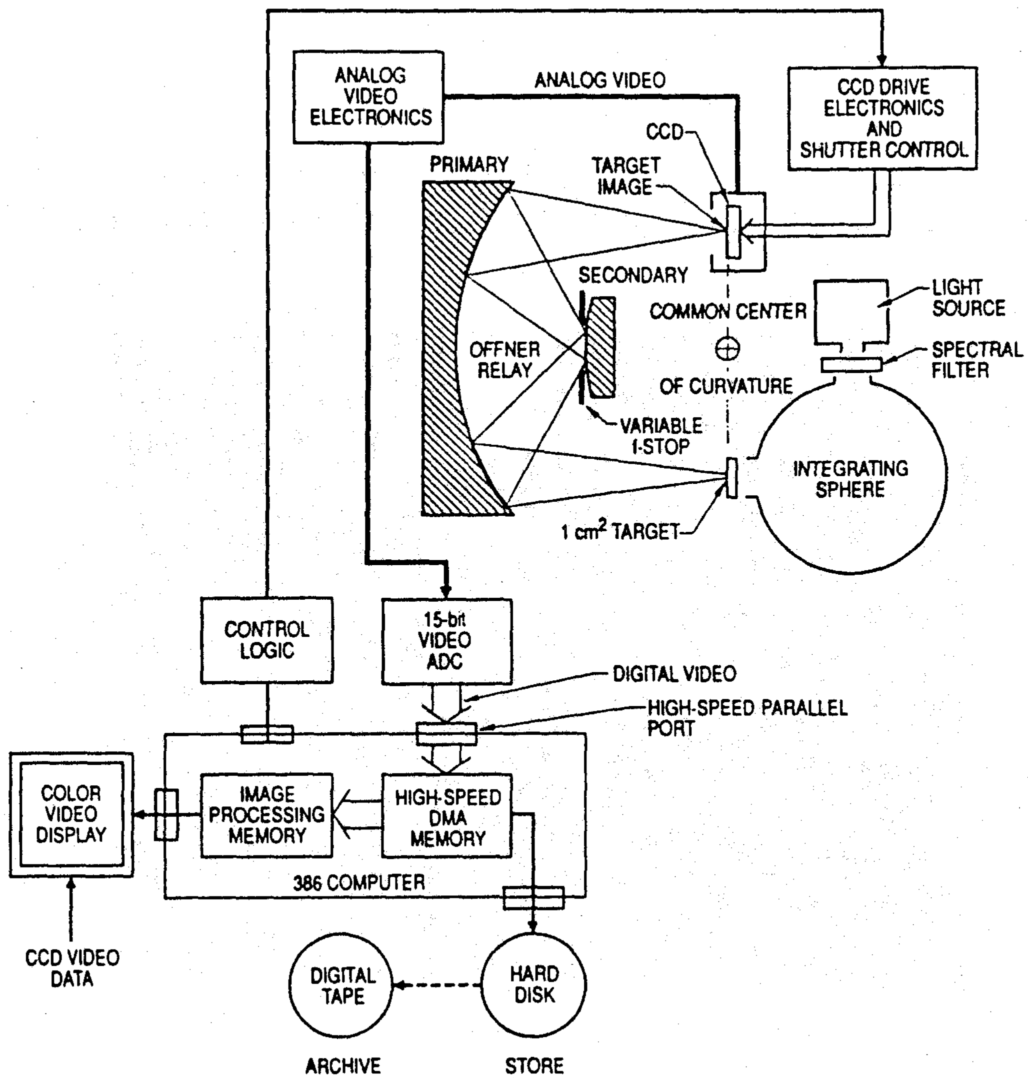
SAME CONFIGURATION AS ABOVE, EXCEPT INDUCED $\Delta V_{MISMATCH}$ = 0.00325 m/sec. ZERO IN $MTF_{MISMATCH}$ OCCURS AT BAR PATTERN 3

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 $\leq 7 \mu M$

BEAT-PATTERN NEAR NYQUIST

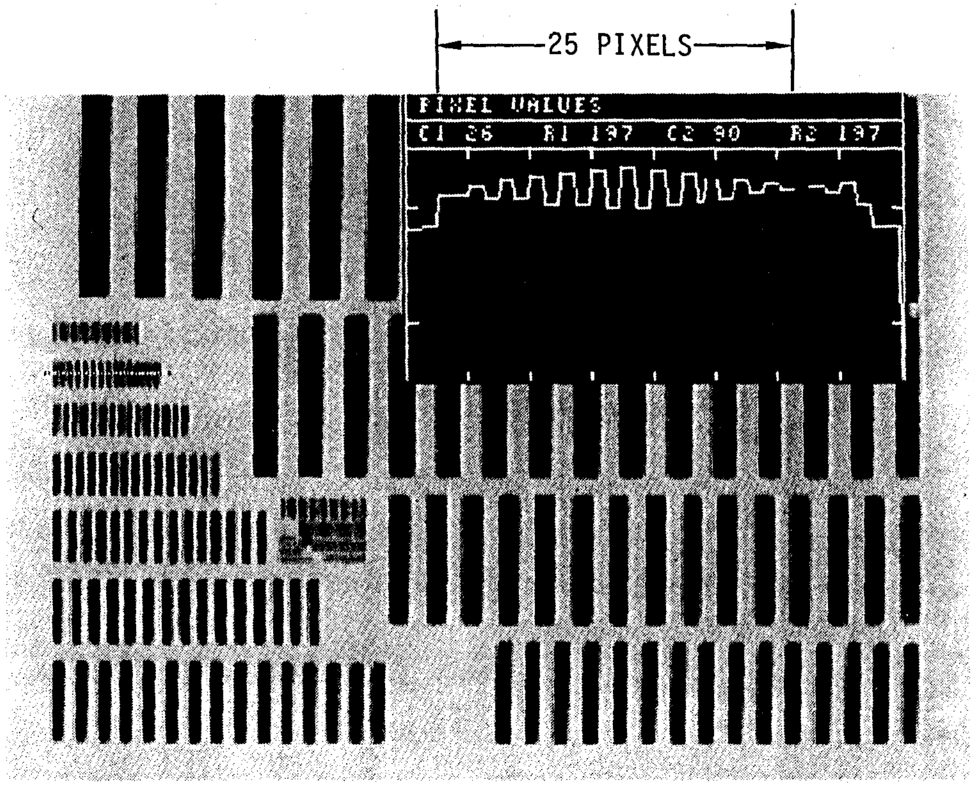


Image profile of the 79.4 lp/mm bar target. The observed beat frequency is precisely that predicted by 1:1 reimaging of that target onto a detector array with a Nyquist frequency of 73.5 lp/mm.

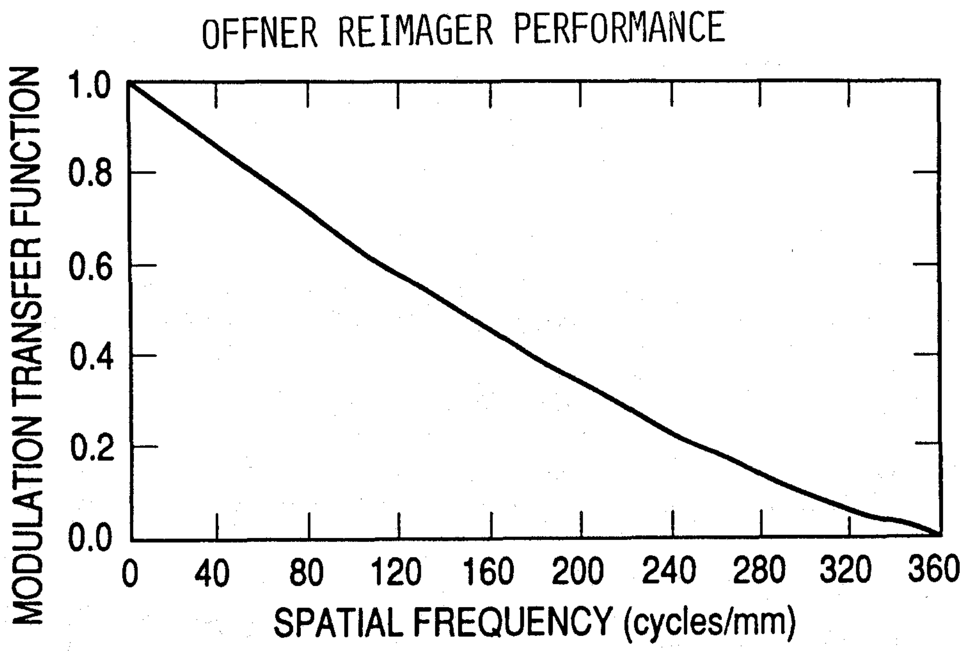
F_N = 73.5 LP/MM

F_{BAR} = 79.4 LP/MM

F_{BEAT} = 5.9 LP/MM

→ COVERS 169 μM

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



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

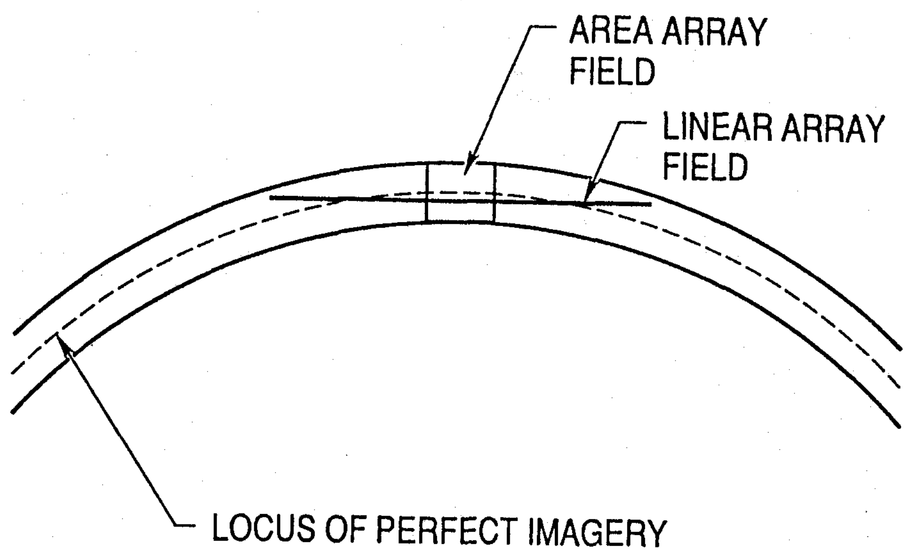
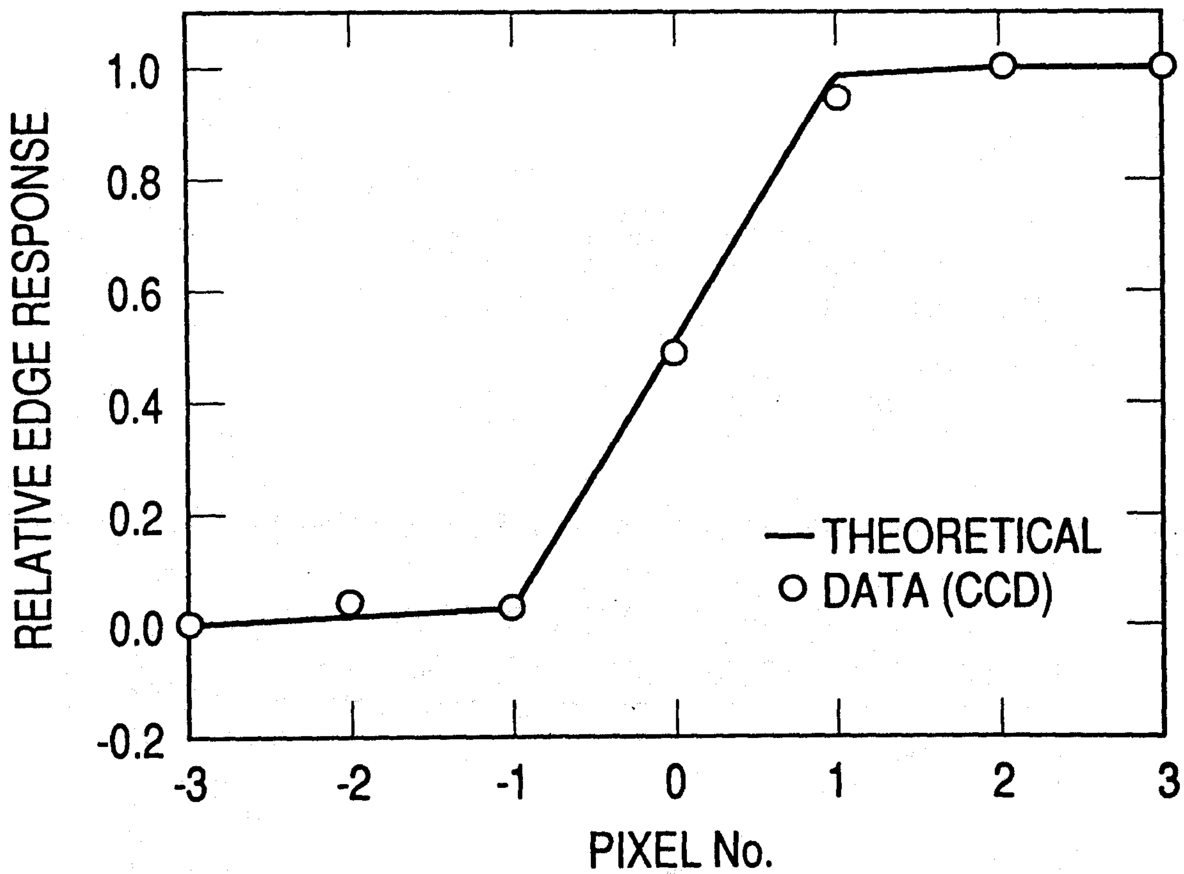


Diagram showing the ability of the "annulus of good imagery" to cover the fields of both area and linear CCd arrays.

EDGE-RESPONSE DATA

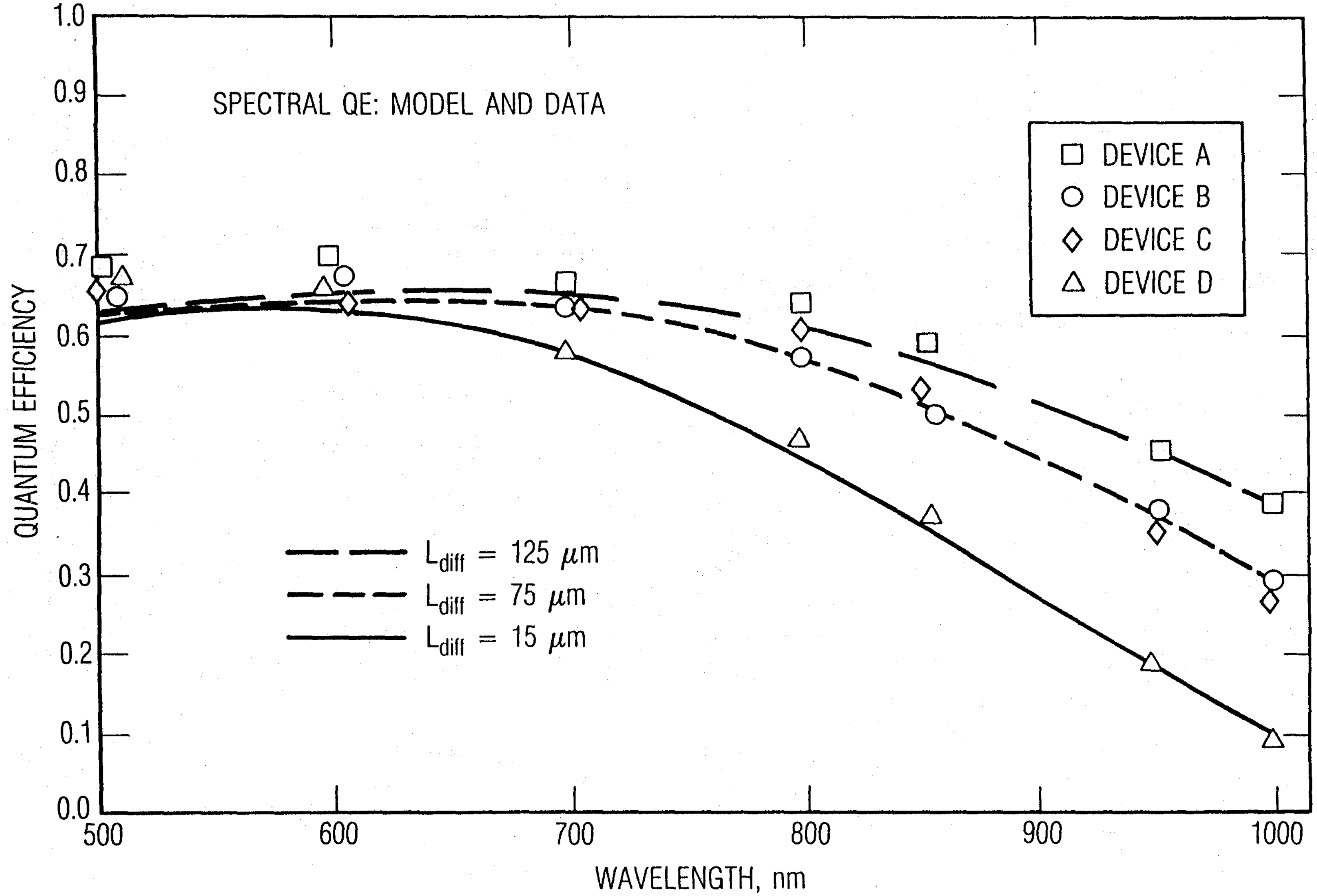


Evidence for diffraction-limited performance of the Offner reimager at f/5 and 550 nm, showing theoretical and experimental responses of a Kodak KAF-1400 CCD to a high-contrast edge.

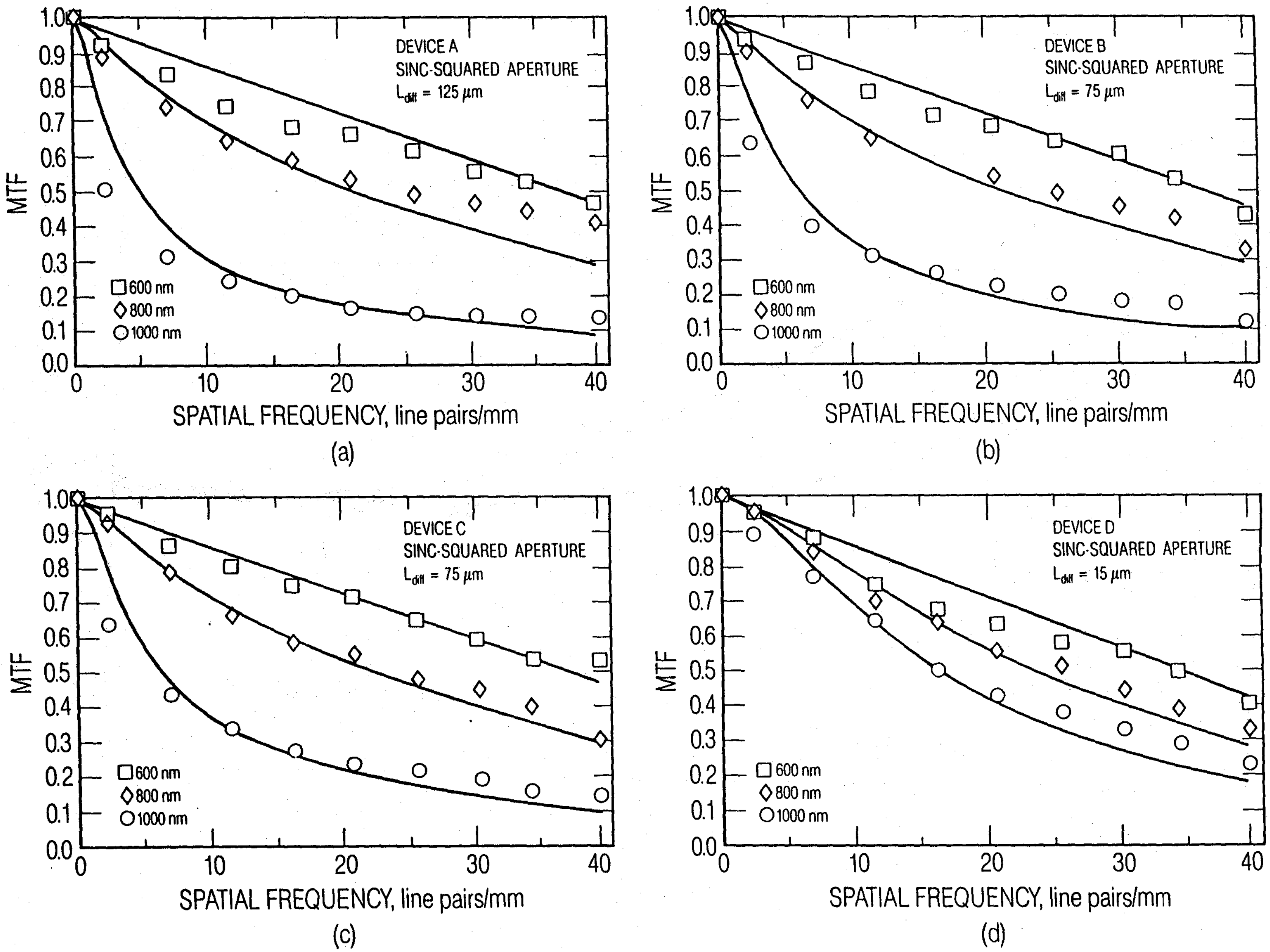
$$ESF(x) = U(x) \otimes PSF_{TOT}(x', y')$$

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

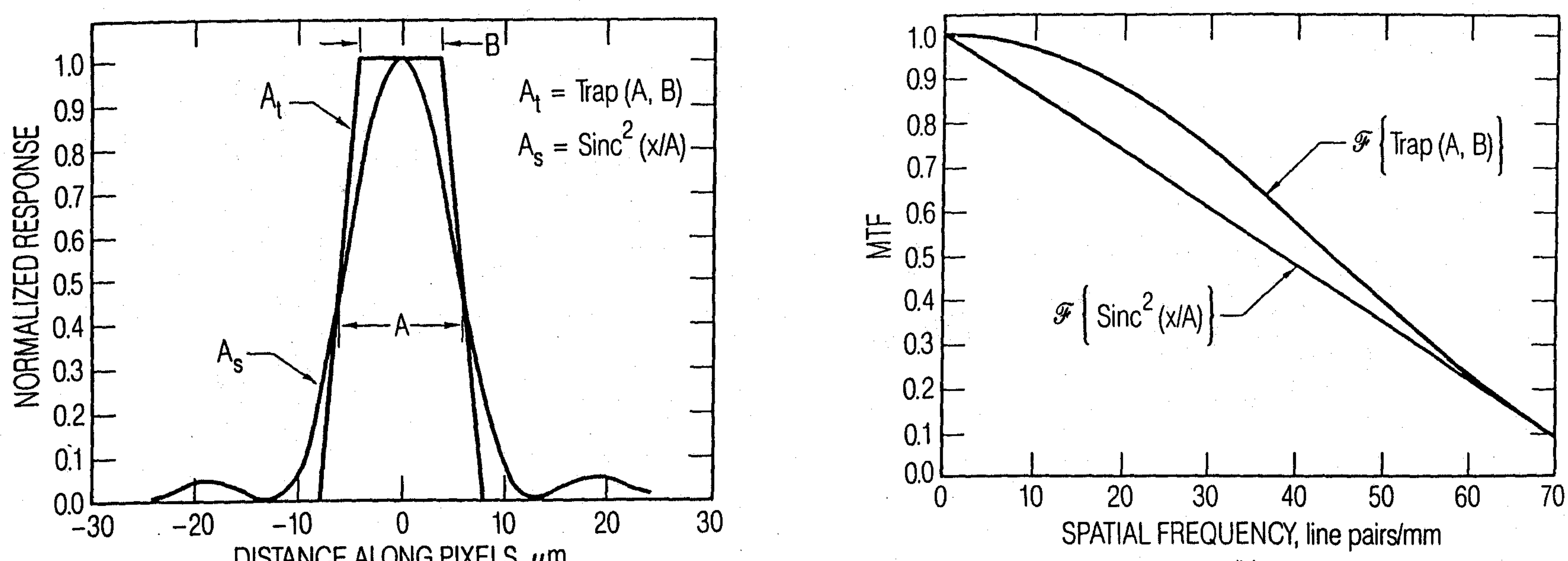
FAIRCHILD LINEAR CCD: SPECTRAL QE DATA



FAIRCHILD LINEAR CCD: SPECTRAL MTF DATA



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



(b)

FAIRCHILD LINEAR CCD: MTF VERSUS DIFFUSION LENGTH