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Detector Array Evaluation and Figures of Merit

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This presentation will review the commonly used methods to evaluate the performance of a two-dimensional focal-plane array using charge transfer devices. Two figures of merit that attempt to combine quantum efficiency, read noise and dark-current generation into a single parameter are discussed. The figures of merit are suggested as possible alternatives to the D*.

DETECTOR ARRAY EVALUATION
AND
FIGURES OF MERIT

STATE OF CONFUSION

- o WHAT WE GET FROM MANUFACTURER
- o WHAT WE WANT
- o WHAT WE TEST FOR

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GENERIC PARAMETERS
QUOTED FROM MANUFACTURER

- o SIZE AND # OF PIXELS
- o D*
- o D* HISTOGRAM
- o READ NOISE HISTOGRAM
- o DARK CURRENT HISTOGRAM
- o SATURATION LEVEL
- o RESPONSIVITY MAP

D* PROBLEMS

- o SMALL AREA DETECTORS (D* = CONSTANT)
- o SPATIAL VARIATIONS ACROSS ARRAY
- o RADIANT "POWER" DEPENDENT FOR PHOTODETECTOR
- o D*(f) - NO 1/f CHARACTERISTIC (i.e., 0.5 Hz)

  SPECIFICATION OF CHOPPER FREQ.
- o WAVELENGTH SPECIFICATION

PARAMETERS WANTED BY USER

- o SPATIAL AVERAGED QUANTUM EFF. vs WAVELENGTH
- o CONVERSION GAIN
- o SPATIAL AVERAGED DARK CURRENT vs INTEGRATION TIME FOR OPERATING TEMPERATURE
- o READ NOISE
- o DEFECTIVE PIXEL MAP
- o DYNAMIC RANGE
- o CROSSTALK
- o FILL FACTOR (DETECTOR AREA)
- o SATURATION LEVEL

TEST/DATA COLLECTED

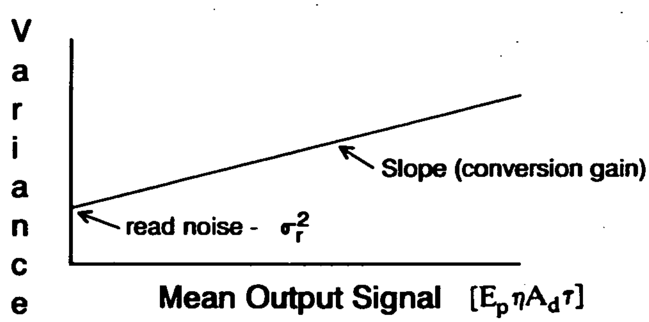
- o MEAN VARIANCE CURVE - σ_r
- o DARK CURRENT GENERATION - Dg
- o SIGNAL MEASURE FOR Q.E. OVER SPECTRAL BAND - η
- o EFFECTIVE DETECTOR AREA - Ad

PLOT SPATIAL MAPS OF:

- DARK CURRENT
- QUANTUM EFFICIENCY
- DEAD PIXELS

MEAN - VARIANCE CURVE

PLOT OF VARIANCE ($NOISE^2$) VERSUS THE MEAN IRRADIANCE (FLAT FIELD) ACROSS ARRAY



$$\sigma^2 = \sigma_r^2 + E_p \eta A_d \tau \text{ (electrons)}$$

COMPUTER PROCESSING

Ep$\propto$ADU (ANALOG - DIGITAL UNITS IN COMPUTER) SO UNITS CAN BE RELATED BETWEEN ADU'S AND FLAT FIELD IRRADIANCE.

MEAN - VARIANCE IN PRACTICE

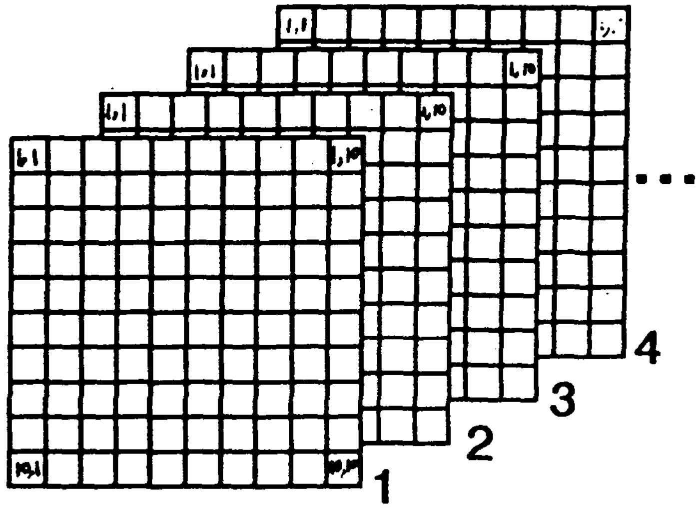
- o TWO WAYS TO CHANGE MEAN IRRADIANCE ON ARRAY
  - VARY INTEGRATION TIME
  - VARY BLACKBODY TEMPERATURE, OR RANGE

[NOT NECESSARILY EQUIVALENT]

IMPORTANCE OF DARK CURRENT

WILL PHOTONS BE DETECTED IN INTEGRATION TIME, OR WILL DARK GENERATED ELECTRONS DOMINATE FOR PARTICULAR APPLICATION?

DARK CURRENT TESTS



FOR VARIOUS INTEGRATION TIMES; ONE TAKES SEVERAL (i.e. 25) FRAMES OF DATA;

A. $\tau \cong 1$ ms (SHORTEST POSSIBLE)

$$\overline{P_{ij}} = \frac{1}{25} \sum_{K=1}^{25} P_{ij}(K)$$; K is Time Index

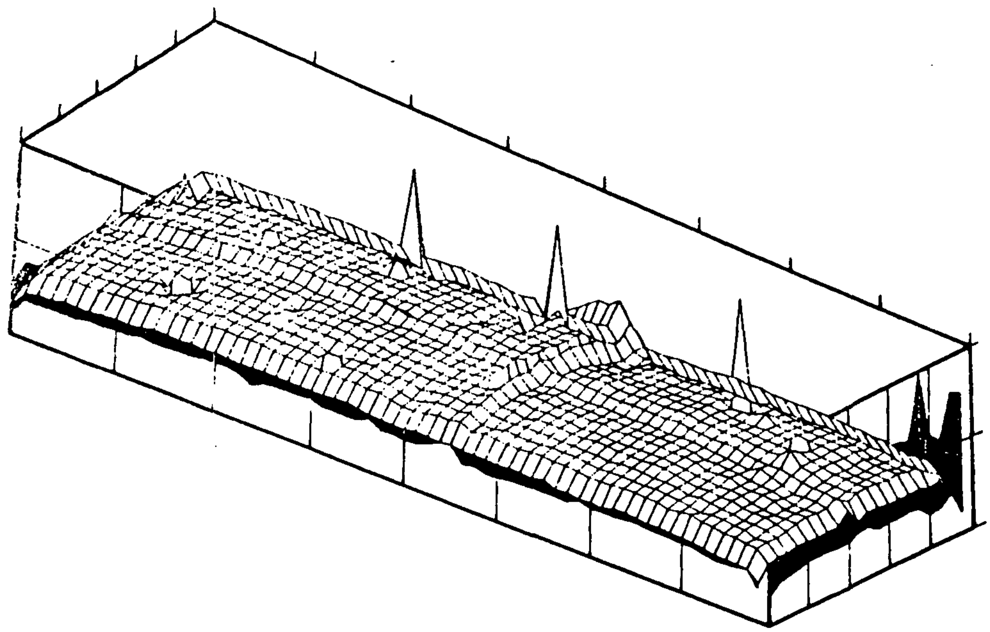
$$F_\tau = \{\overline{P}_{11}, \overline{P}_{12}, \overline{P}_{13} \ldots \overline{P}_{ij}\}$$ Average Dark Frame

B. $\tau >> 1$ ms

(REPEAT)
FIND THE DARK FRAME VALUE FOR SEVERAL INTEGRATION TIMES

DARK FRAME ANALYSIS

- o LOCATE A WELL BEHAVED REGION
- o READ NOISE VALUE IS FOUND @ SHORT INTEGRATION TIMES



DARK CURRENT GENERATION RATE
Dg (# OF e^- /SEC-PIXEL)

INCLUDES OTHER SOURCES

- o LIGHT LEAKS
- o "SELF-EMISSION" OF ELECTRICAL COMPONENTS

FIGURES OF MERIT

IR SENSOR

- SCANNER SYSTEM
  - NETD (LLoyd)
  - MRT (LLoyd)
  - SINGLE DETECTOR
    - D*
    - D**
- STARING
  - HI BACKGROUND
    - *NETD
    - MRT
    - M (Birtley)
    - *CSNR (Mooney)
    - ARRAY
      - *2-D*
  - LOW BACKGROUND
    - NEI (Kohn)
    - ARRAY
      - DQE (Nudelman/Shaw)
        - σ_r - read
        - D_g - dark
        - η - QE
        - U - nonuniformity

ARRAY TESTING AND FIGURE OF MERIT ARE APPLICATION DEPENDENT

* RELATED

NON-UNIFORMITY DEFINITION

$$U(Ep) = \frac{\text{r.m.s. SPATIAL VARIATION IN ARRAY OUTPUT}}{\text{SPATIALLY AVERAGED ARRAY OUTPUT}}$$

$$= \frac{\sigma_{\bar{P}_{ij}}}{\langle \bar{P} \rangle}$$

SPATIAL AVERAGE

$$\langle \bar{P} \rangle = \frac{1}{NM} \sum_{i}^{M} \sum_{j}^{N} \bar{P}_{ij}$$

SPATIAL VARIANCE

$$\sigma^2_{\bar{P}_{ij}} = \frac{1}{NM} \sum_{i}^{N} \sum_{j}^{M} [\bar{P}_{ij} - \langle \bar{P} \rangle]^2$$

- o U (Ep) CAN BE IMPROVED THROUGH USE OF A NON-UNIFORMITY CORRECTOR
- o U (Ep) IS TYPICALLY REDUCED TO ZERO AT SYSTEM CALIBRATION POINTS.

ARRAY FIGURE OF MERIT

- o 2-D* IS A D* PLUS THE RANDOM CONTRIBUTION OF NON-UNIFORMITY, READ NOISE, AND DARK CURRENT
- o A MODIFIED D* CALLED 2-D* MAY BE USED IN LLOYDS NETD EXPRESSION TO YIELD CSNR

$$2 - D^* = \frac{\lambda}{hc} \sqrt{\frac{\eta}{2\left[E_p + \frac{\sigma_r^2}{A_d \eta \tau} + E_p^2 A_d \eta \tau U^2 + \frac{D_g}{A_d \eta}\right]}}$$

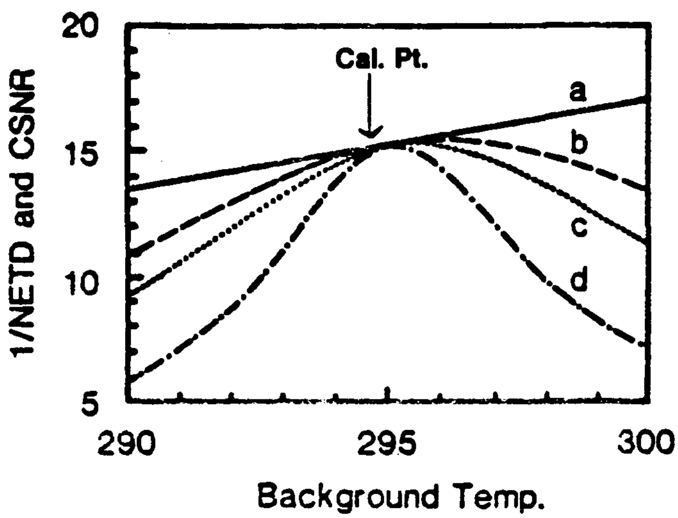
- o PHOTON SHOT NOISE - Ep
- o READ NOISE - σ_r
- o SPATIAL PATTERN - u
- o DARK CURRENT GENERATION (ZERO) - Dg

HIGH BACKGROUND CONTRAST SIGNAL-TO-NOISE RATIO (CSNR)

$$CSNR = \frac{\partial[E_p \eta A_d \tau]/\partial T}{[E_p \eta A_d \tau + \sigma_r^2 + E_p^2 \eta^2 A_d^2 U^2 \tau^2]^{1/2}}$$

- **Ep** = PHOTON IRRADIANCE (P/s-cm^2)
- **η** = QUANTUM EFF.
- **Ad** = PIXEL AREA
- **τ** = INTEGRATION TIME
- **σ_r** = READ NOISE
- **U** = RMS NON-UNIFORMITY
- **T** = TEMPERATURE

CSNR vs BACKGROUND TEMPERATURE FOR VARIOUS AMOUNTS OF RESIDUAL NON-UNIFORMITY



a. NO NON-UNIFORMITY; CSNR = 1/NETD

b. u = 1%

c. > b

d. > c

UNIFORMITY CORRECTION IS LIMITED BY QUANTIZATION NOISE OF A/D CONVERTER

ARRAY TESTING IS APPLICATION DEPENDENT
THEREFORE, FIGURES OF MERITS VARY

- o **HIGH BACKGROUND SENSOR SYSTEM**

  NETD - NOISE EQUIV. TEMP. DIFFERENCE

  MRT - MINIMUM RESOLVABLE TEMPERATURE

  CSNR - CONTRAST SIGNAL-TO-NOISE RATIO

- o **LOW BACKGROUND SENSOR SYSTEM**

  NEI - NOISE EQUIV. IRRADIANCE [PHOTONS/SEC-CM ^{2}]

  DQE - DETECTIVE QUANTUM EFFICIENCY

Detective Quantum Efficiency - DQE (single detector)

$$DQE \equiv \frac{(S/N)^2_{meas}}{(S/N)^2_{in}} \qquad \text{iff BLIP; } \eta$$

Apply to a 2-dimensional array

$$(S/N)_{in} = \sqrt{E_p A_d \tau}$$

$$(S/N)_{meas} = \frac{E_p A_d \tau \eta}{[E_p A_d \eta \tau + \sigma_r^2 + (E_p A_d \eta \tau U)^2 + D_g \tau]^{1/2}}$$

↑ shot ↑ read ↑ uniformity ↑ dark generation

2-Dimensional DQE

$$2\text{-}DQE = \frac{(S/N)^2_{meas}}{(S/N)^2_{in}} = \frac{1}{\frac{1}{\eta} + \frac{\sigma_r^2}{E_p A_d \eta^2 \tau} + E_p A_d \tau U^2 + \frac{D_g}{E_p A_d \eta^2}}$$

iff E_p is large enough to produce shot noise,
or U, σ_r, and D_g are small,
DQE is equal to quantum efficiency.

SAMPLE CALCULATION

$\eta = 0.6$

$N_{full} = 10^6$

$A_d = (50\ \mu m)^2$

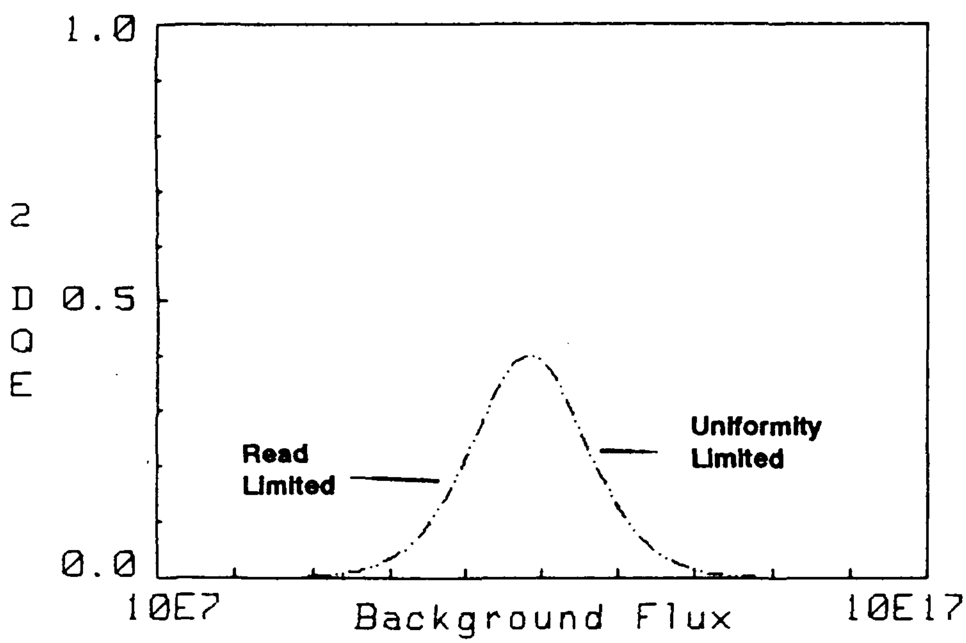
$\tau = 0.001$ sec

$\sigma_r = 50\ e^-$

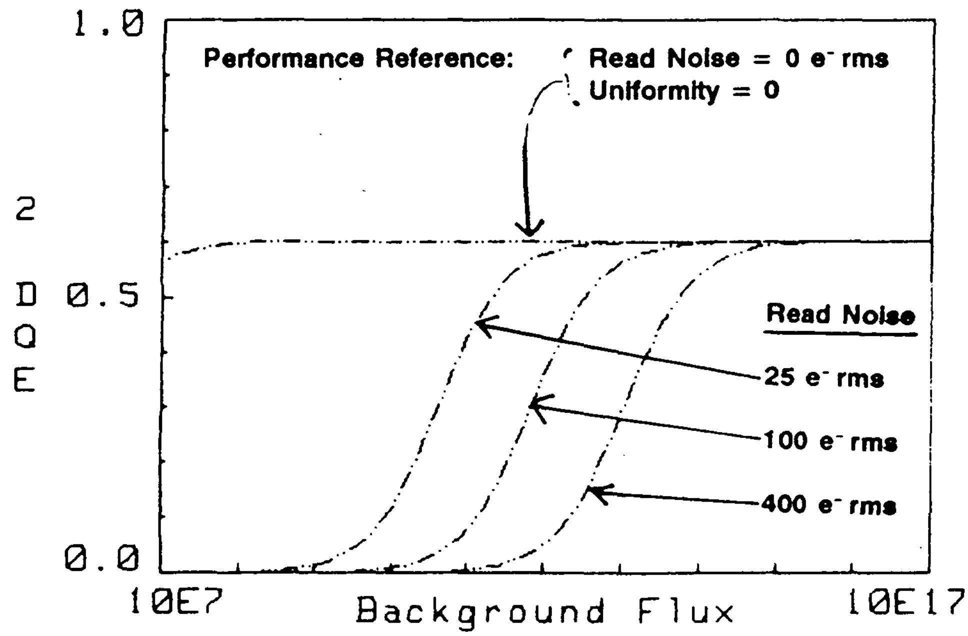
$D_g = 10 e^-/\text{sec-pixel}$

$U = 0.005$

$$2 - DQE = 1/(\frac{1}{0.6} + \frac{2.79(10^{11})}{E_p} + E_p\ 6.25(10^{-13}) + \frac{1.11(10^6)}{E_p})$$



READ NOISE INFLUENCE



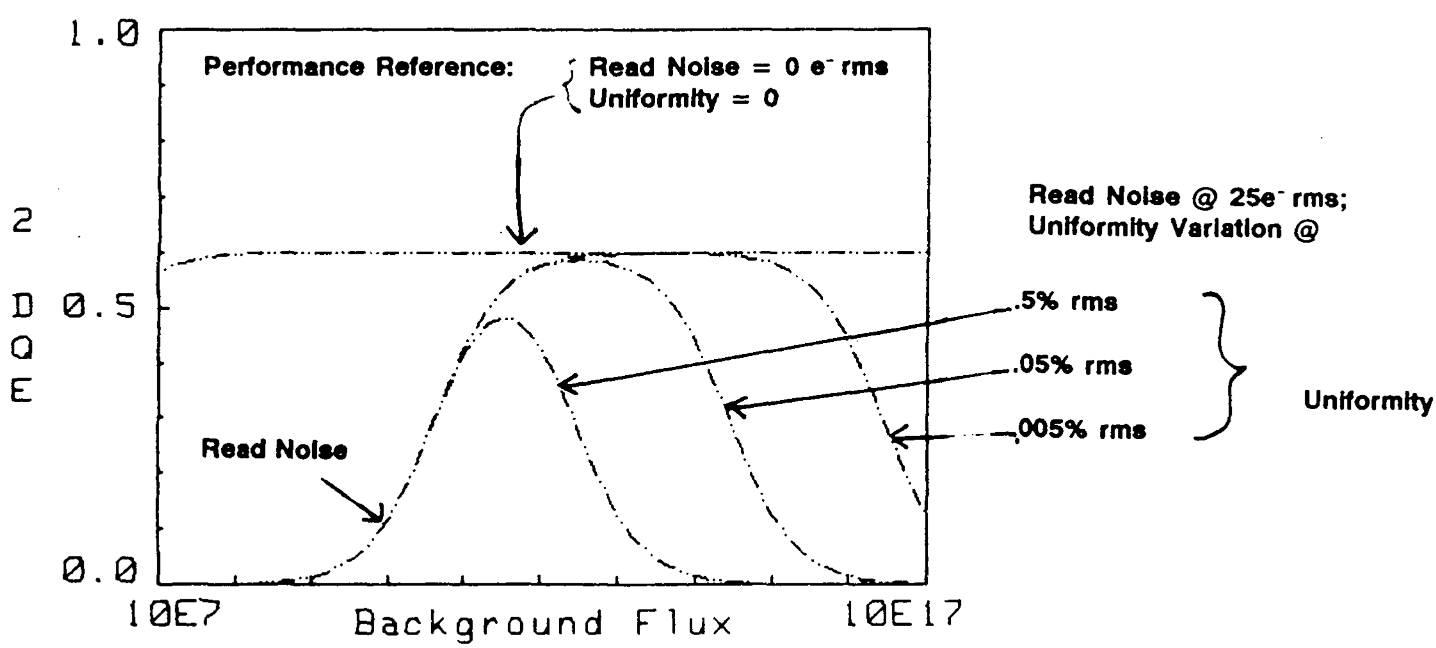
η = .60

τ = .001 sec

Ad = $(50\mu m)^2$

Dg = 10e⁻ /sec-pixel

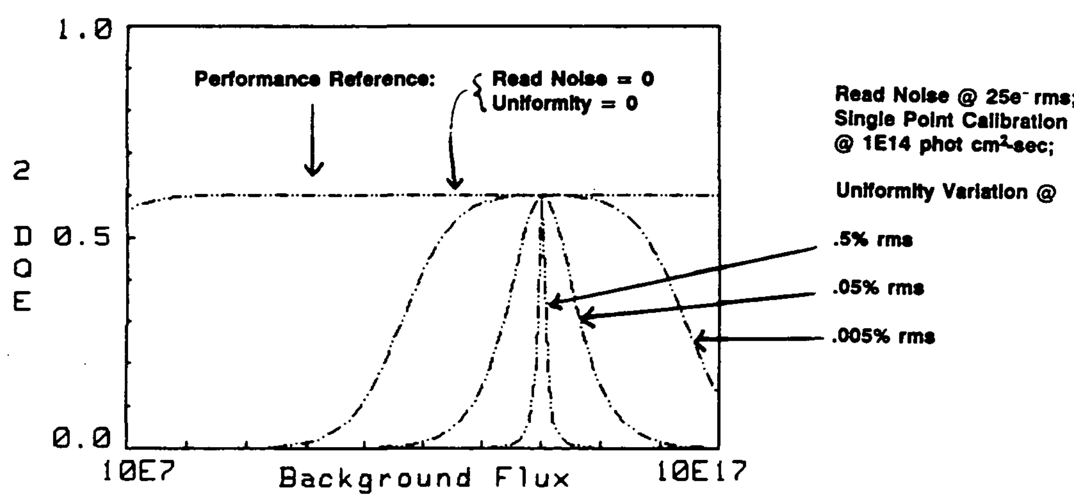
NON-UNIFORMITY INFLUENCE



WHERE DOES SPATIAL NON-UNIFORMITY COME FROM

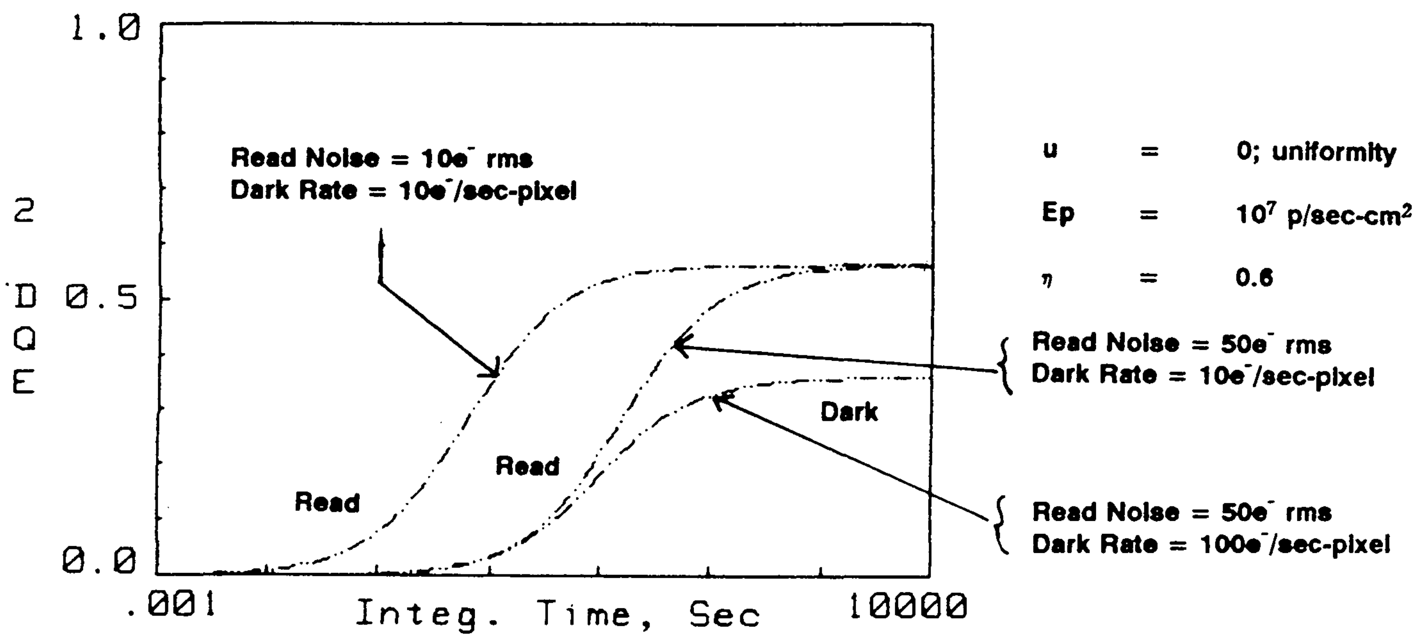
- VARIATIONS IN DARK CURRENT DENSITY
- VARIATIONS IN DETECTOR ACTIVE AREA
- VARIATIONS IN THE ABSOLUTE VALUE, OR IN SOME CASES, VARIATIONS IN THE SPECTRAL SHAPE, OF THE QUANTUM EFFICIENCY CURVE.
- VARIATIONS IN THE DETECTOR-TO-DETECTOR NON-LINEARITY OF RESPONSE
- VARIATIONS IN THE 1/f NOISE ASSOCIATED WITH EACH DETECTOR OR OTHER UNIT-CELL ELECTRONICS.

FLAT FIELD CALIBRATION EFFECTS



DARK CURRENT EFFECTS

$$2 - DQE = \frac{1}{\frac{1}{0.6} + \frac{27.7}{\tau} + 1.1(10^{-2})D_g}$$



DARK CURRENT SIMPLY LIMITS THE MAXIMUM DETECTIVE QUANTUM EFFICIENCY

- GOOD (↑) DQE REQUIRES "LOW" READ NOISE AND "LOW" DARK CURRENT

CONCLUSIONS

TESTS ON ARRAYS

- o MEAN VARIANCE
- o DARK CURRENT GENERATION FRAMES
- o SIGNAL MEASUREMENTS FOR Q.E. VALUES
- o EFFECTIVE DETECTOR AREA

FIGURES OF MERITS FOR FPA

- o 2-D* (CSNR - CONTRAST SIGNAL TO NOISE) RATIO
  - GOOD FOR HIGH BACKGROUNDS AND CALIBRATION ONCE AN HOUR
- o DQE (DETECTIVE QUANTUM EFFICIENCY)
  - GOOD FOR LOW BACKGROUNDS
  - COMBINES READ NOISE, DARK CURRENT, QUANTUM EFFICIENCY AND NON-UNIFORMITY INTO ONE PARAMETER