McLean Sec.9-9.2

Misato Fujii

9 Characterization and calibration of array instruments

・all imaging devices require calibration to be used for quantitative work

- ・how the properties of the detector are measured
- ・how the detector affects analysis

→・describe steps in the calibration of CCD and other array detectors

- ・signal-to-noise expressions for array instruments

9.1 FROM PHOTONS TO MICROVOLTS

- observed quantity : stream of photons
- detected quantity : small voltage(V_0) →amplified and digitized
- N_p photons are absorbed → $\eta G N_p$ electrons will be detected
  $\eta(< 1)$: quantum efficiency, $G(\sim 1)$: photoconductive gain
  - multiple by the charge on the electron e
    →total number of coulombs of charge detected
    →voltage at the output pin of the array detector $V_0 = \frac{A_{SF}\eta G N_p e}{C}$
    C: capacitance of the output node of the detector
    $A_{SF}(\sim 0.8)$: amplification or gain of the output amplifier (source follower)

⇨first step : determine the quantum efficiency or QE

9.1.1 Quantum efficiency and DQE

QE can be determined with a calibration system constructed to illuminate the detector through a known spectral passband

1. source of illumination: incandescent lamp, grating spectrometer
2. integrating sphere: randomize the light rays and produce a uniformly illuminated source
   ・longer wavelength→blackbody source can be used instead of the integrated sphere
3. shutter and filter
4. mirror: split the light toward the detector cryostat and a calibrated photodiode
5. record the signal from the calibrated photodiode and obtain relative QE as a function of wavelength

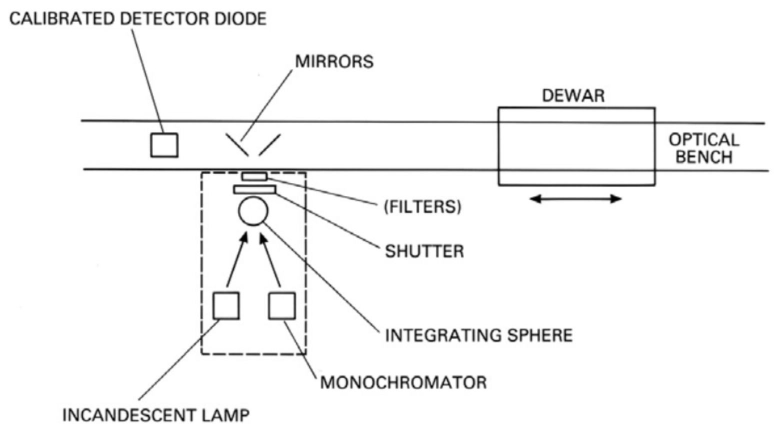

Figure 9.1. A possible laboratory arrangement for calibration and characterization of CCDs.

9.1.1 Quantum efficiency and DQE

- convert to absolute QE: require a precise calibration of illumination
  - exact transmission or profile of the filter passband
    - measured in commercial spectrophotometers
  - accurate determination of the solid angle on the source subtended by a pixel
    - easy to obtain solid angle with a geometry controlled by baffles

9.1.1 Quantum efficiency and DQE

- the measured QE of a deep-depletion CCD
  - good agreement between 1-R and QE(η) except at the short and long ends of the wavelength
    - R: reflectance
    - shortest wavelength:
      electron-hole are created too far from the depletion region
    - longest wavelength:
      absorption length are too long and no electron-hole pairs are created

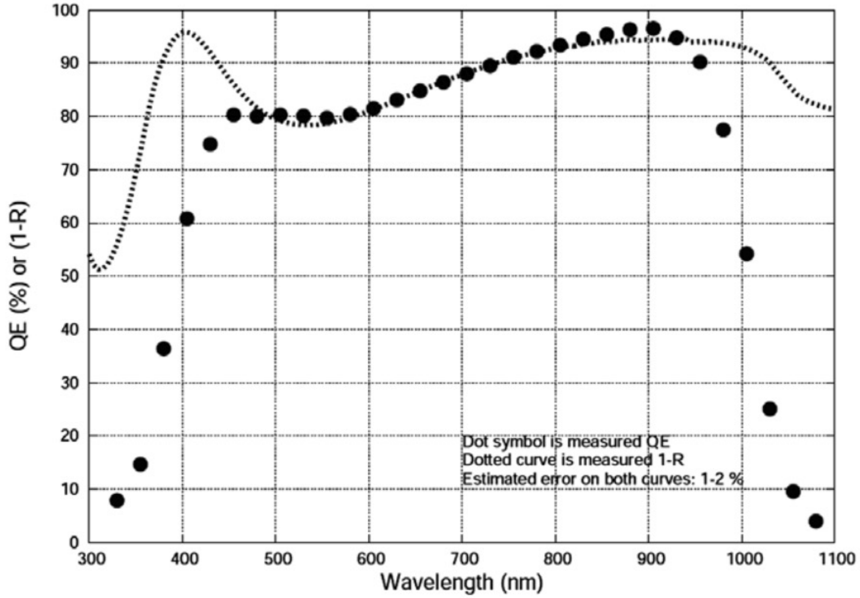

Figure 9.3. Curves of the measured QE and reflectance of a deep-depletion CCD using the UCO/Lick automated system. Credit: Richard Stover.

9.1.1 Quantum efficiency and DQE

・measure A_{SF}

・change the output drain voltage and observe the change in the output source voltage

→ratio = A_{SF}

・measure C

・$C = \frac{Q}{V}$ (Q: controlled charge, V: measured voltage)

・expose the detector to a substantial light level and obtain a large output signal

→dominant noise is photon noise

・measured voltage: $V = \frac{eN}{C}$ (N: total number of collected charge)

・voltage noise: $\sigma_V = \frac{e\sqrt{N}}{C}$

⇨$C = \frac{eV}{\sigma_V^2}$

9.1.1 Quantum efficiency and DQE

・DQE(detective quantum efficiency): QE of an idealized imaging system with no readout noise but which produces S/N ratio as the actual CCD

・S/N ratio for a CCD pixel

$$\frac{S}{N} = \frac{\eta N_p}{\sqrt{(\eta N_p + R^2)}}$$

N_p: total number of photons incident on the pixel

R: rms value of the readout noise

・ideal detector with no readout noise

$$\frac{S}{N} = \sqrt{\eta' N_p}$$

→DQE: $\eta' = \eta \frac{1}{\left(1+\frac{R^2}{\eta N_p}\right)} < \eta$

・dependent on N_p

Table 9.1. Detective quantum efficiency (DQE) as a function of readout noise R (electrons rms) and number of incident photons N_p for two values of the true QE (30% and 60%).

Read noise $R(e^-)$	*Incident number of photons* (N_p)					
	1	*10*	*100*	*1,000*	*10,000*	*100,000*
1	6.9 (22.5)	22.5 (51.4)	29.0 (59.0)	29.9 (59.9)	30.0 (60.0)	30.0 (60.0)
10	0.1 (0.4)	0.9 (3.4)	6.9 (22.5)	22.5 (51.4)	29.0 (59.0)	29.9 (59.9)
100	0.001 (0.004)	0.009 (0.215)	0.1 (0.4)	0.9 (3.4)	6.9 (22.5)	22.5 (51.4)

9.1.2 Photon transfer function

・digital signals actually recorded by CCD : called data numbers (DNs) or analog-to-digital units (ADUs)

・must be turned back into microvolts→electrons→photons

・actual data counts or DN recorded by CCD are related to the numbers of electrons in the charge packets

$$S = \frac{(N_e + N_d)}{g} + b$$

S: recorded output signal in DNs

N_e: number of electrons in the charge packet (ηN_p)

g: system photon transfer gain factor (electrons/DN)

b: electronic offset or bias level for an empty charge packet

N_d: residual dark current signal

9.1.2 Photon transfer function

・measure g

・calculate from the overall amplifier gain and the capacitance of CCD

$$g = \frac{V_{fs}C}{2^n A_g e}$$

V_{fs}: the full-scale voltage swing allowed on the A/D unit

n: the number of bits to which the A/D can digitize

⇨voltage corresponding to 1DN at the A/D unit : $V_{fs}/2^n$

A_g: the total product of all the amplifiers in the system

C: CCD capacitance

9.1.2 Photon transfer function

・obtain several exposures of a flat-field and examine the mean signal and noise from every pixel independently (or the mean signal from a small array of pixels)

$$S_M = \frac{1}{n}\sum X_i\,, \quad V_M = \frac{\sum (X_i - S_M)^2}{n-1}$$

S_M: mean of dark/bias-subtracted signal

V_M: variance signal

X_i: data stream(count)

9.1.2 Photon transfer function

・ total noise: $(\mathrm{noise})^2 = p^2 + R^2$

p: photon noise on the signal photoelectrons

R: readout noise in electrons from the CCD output amplifier

→convert from electrons to DN

$$\left(\frac{\mathrm{noise}}{g}\right)^2 = \left(\frac{p}{g}\right)^2 + \left(\frac{R}{g}\right)^2$$

・ $V_M = \left(\frac{\mathrm{noise}}{g}\right)^2$, $p = \sqrt{gS_M}$（ポアソン統計, gS_M: mean number of photoelectrons）

$$V_M = \frac{1}{g} S_M + \left(\frac{R}{g}\right)^2$$

9.1.2 Photon transfer function

- $V_M = \frac{1}{g} S_M + \left(\frac{R}{g}\right)^2$
  - gradient: $m = \frac{1}{g}$, $V_M = \left(\frac{R}{g}\right)^2 (S_M = 0)$

    $\rightarrow g,\ R$
  - show where the CCD or IR array begins to become non-linear and saturate
  - lowest signals→noise is dominated by the fixed readout noise
  - larger signals→dominated by photon noise

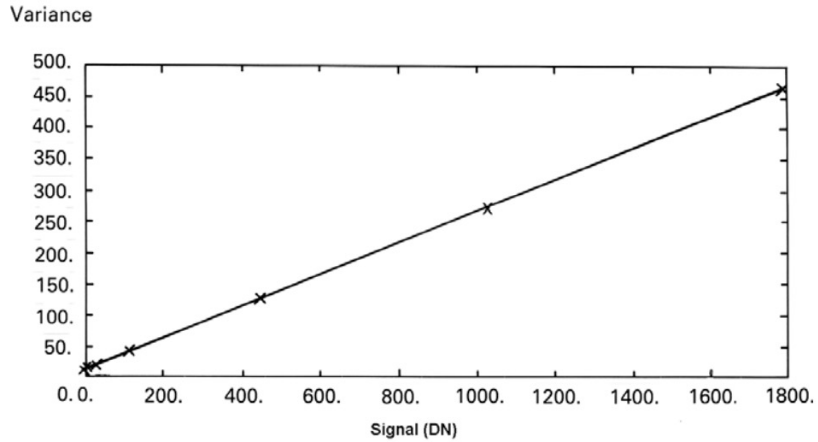

Figure 9.4. A plot of variance (noise-squared) vs. signal in data numbers showing the expected linear graph.

9.2 NOISE, BIAS, AND DARK CURRENT

・bias level (b in $S = \frac{(N_e + N_d)}{g} + b$): small positive reading for each pixel produced by the CCD in the no-signal conditions

・determined by a frame with zero exposure time and shutter closed

・take many bias frames and use the median of that set

→subtract from exposed frame, as the first step of data reduction

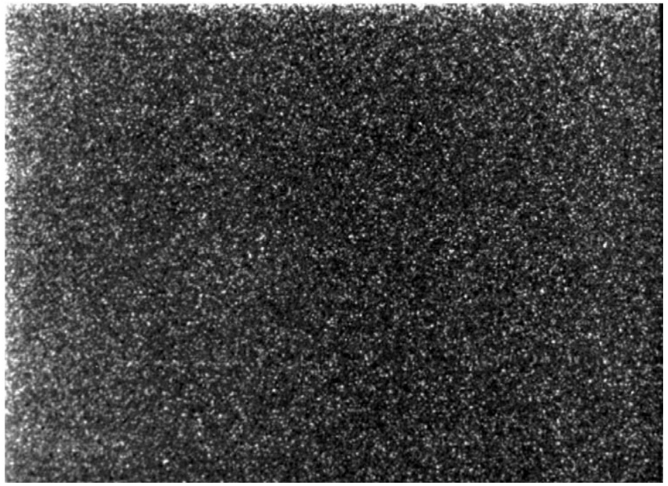

Figure 9.6. A clean bias frame showing no serious amplifier fixed pattern noise or faint diagonal bars due to ground-loop interference.

9.2 NOISE, BIAS, AND DARK CURRENT

・bias: also obtained by using an overscan

　・send more pulses than required to vertically and horizontally read out the CCD (1,034 × 1,034 instead of 1,024 × 1,024)

　　・the outside area should only contain bias level signals, provided the CTE of the device is good

　　・derive offset of overscan in the bias frame and astronomical object frame

　　　→average and subtract from the object frame

9.2 NOISE, BIAS, AND DARK CURRENT

- noise
  - if the system is perfect and a bias frame doesn't contain fixed pattern structure
    - random readout noise variations dominate
    - standard deviation of the array detector
      →readout noise R/g
  - if there is some unavoidable fixed pattern in the bias frame
    - take the difference between two bias frames
    - measured noise distribution $\sigma = \sqrt{2}R/g$

9.2 NOISE, BIAS, AND DARK CURRENT

- dark current
  - determined by long exposures with the CCD shutter closed
    - exposure time: 1h might be needed to determine sufficiently accurate dark current
    - several exposures enable cosmic-ray and radioactivity events to be counted
  - more significant in infrared array