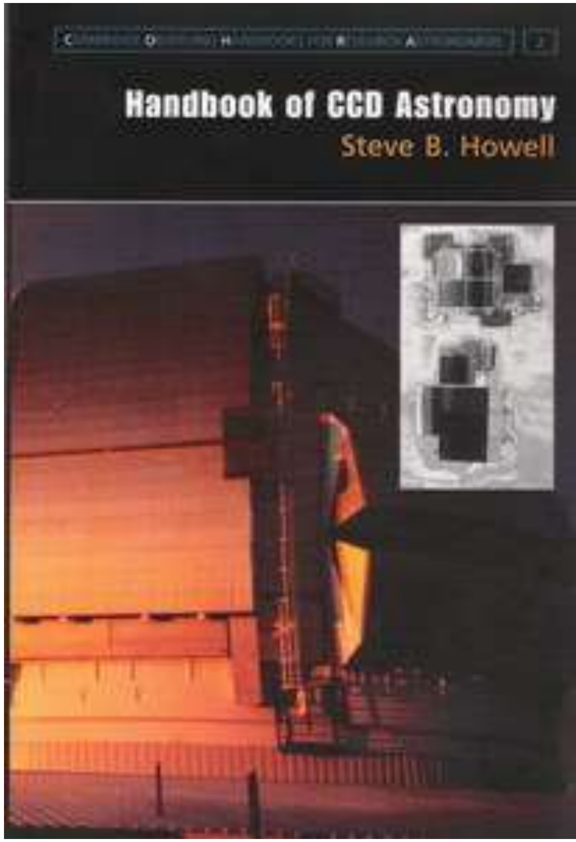
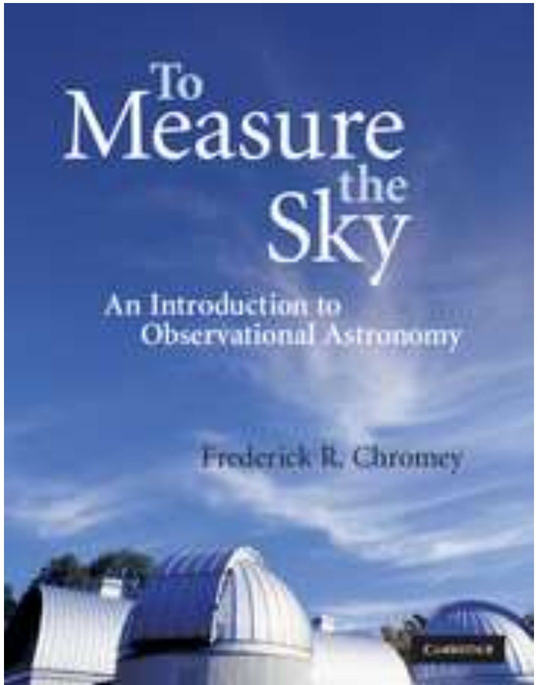
AGA0414
CCDs, data reduction, noise

- *To Measure the Sky*
- *Handbook of CCD astronomy*
- *Introduction to CCDs:*

astro.kent.ac.uk/~df/teaching/ph507/tel_4.pdf



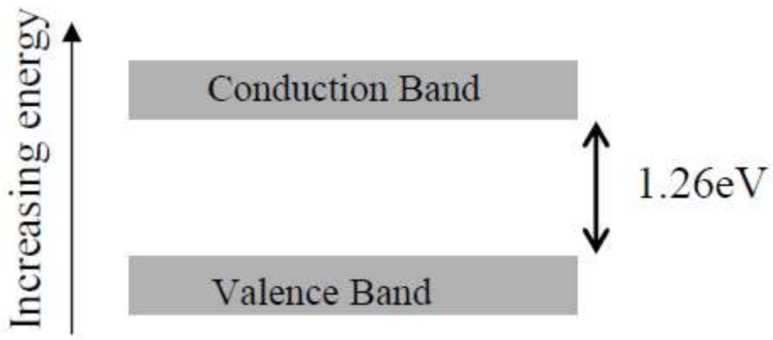
Prof. Jorge Meléndez

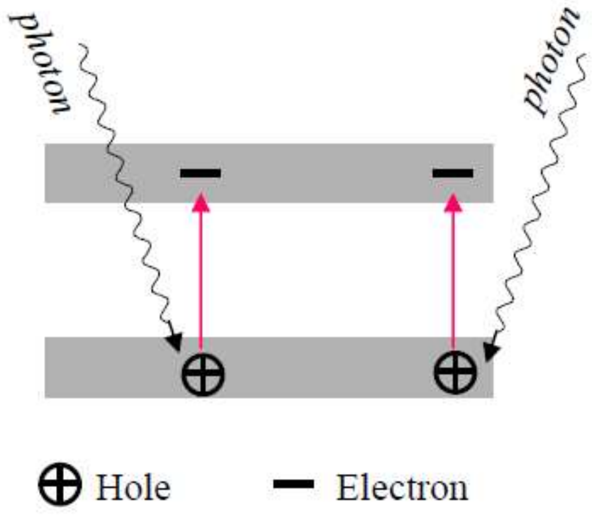


CCDs: Introduction

- 1921: Nobel Prize for photoelectric effect (Einstein)
- 1969: William Boyle & George Smith
- 1975: Primeira imagem astronômica
- 2009: Prêmio Nobel de Física para William Boyle & George Smith

Silício requer ≥ 1,26 eV para excitar o elétron para a banda de valencia





Leitura de CCDs

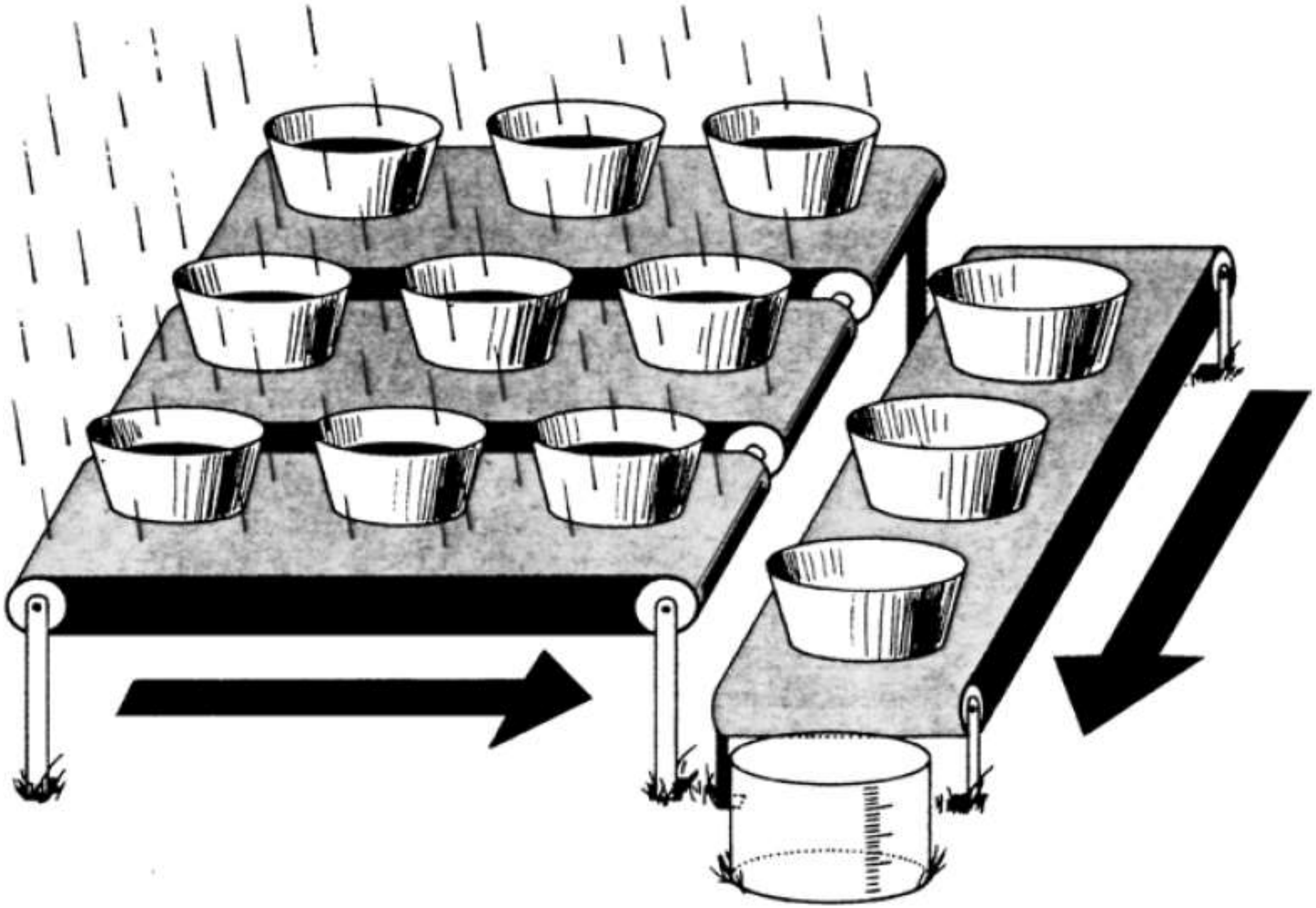
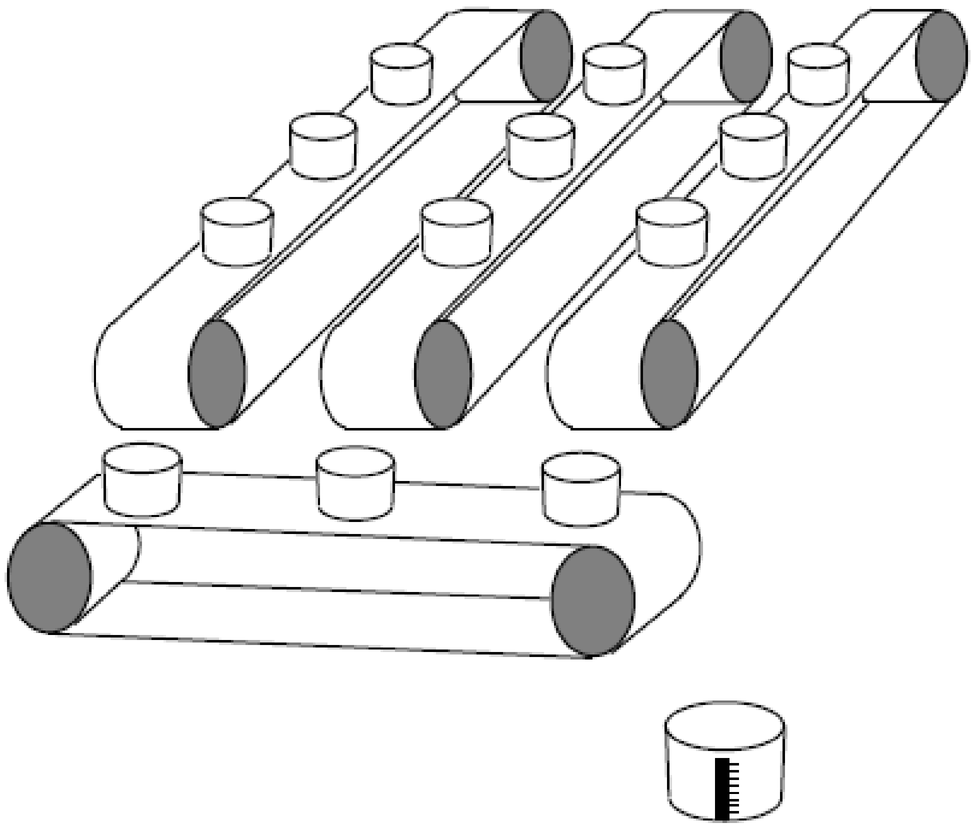


Fig. 2.1. CCDs can be likened to an array of buckets that are placed in a field and collect water during a rainstorm. After the storm, each bucket is moved along conveyor belts until it reaches a metering station. The water collected in each field bucket is then emptied into the metering bucket within which it can be measured. From Janesick & Blouke (1987).

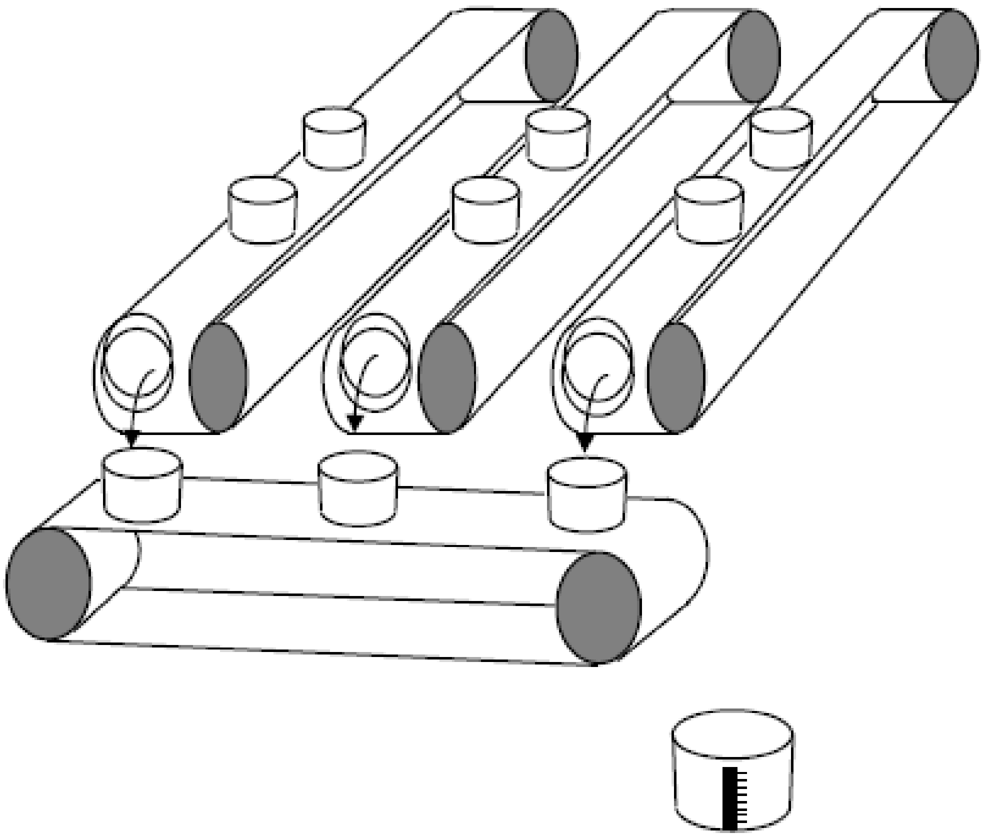
Leitura de CCDs

Exposure finished, buckets now contain samples of rain.



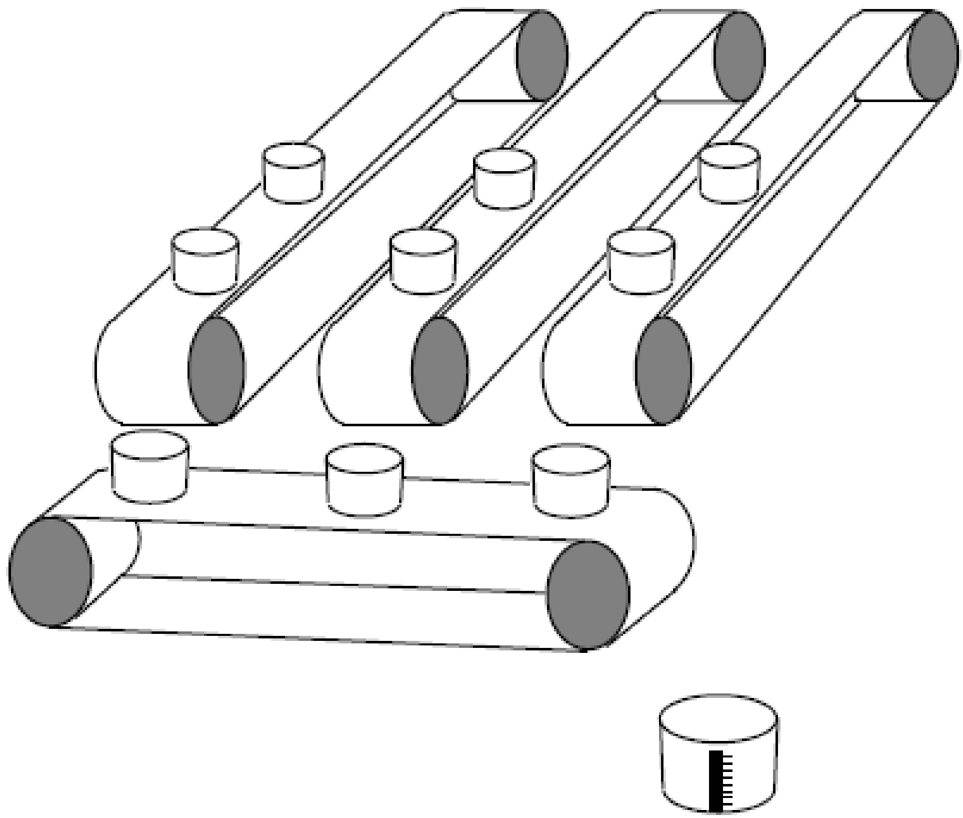
Leitura de CCDs

Conveyor belt starts turning and transfers buckets. Rain collected on the vertical conveyor is tipped into buckets on the horizontal conveyor.



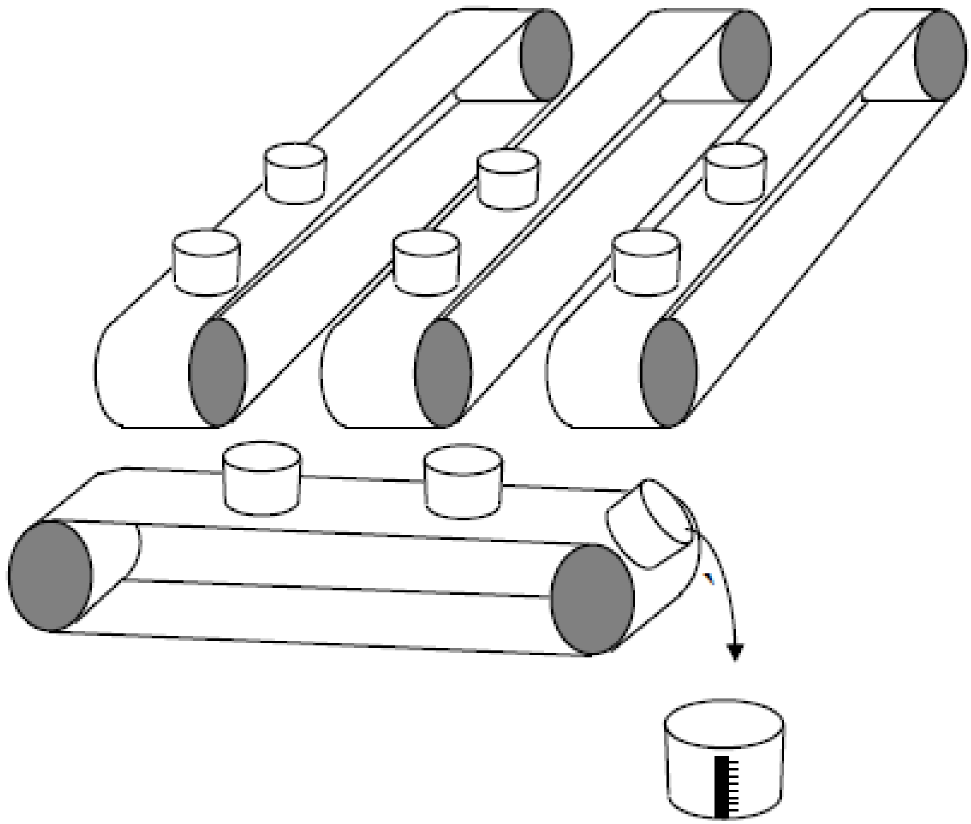
Leitura de CCDs

Vertical conveyor stops. Horizontal conveyor starts up and tips each bucket in turn into the measuring cylinder .

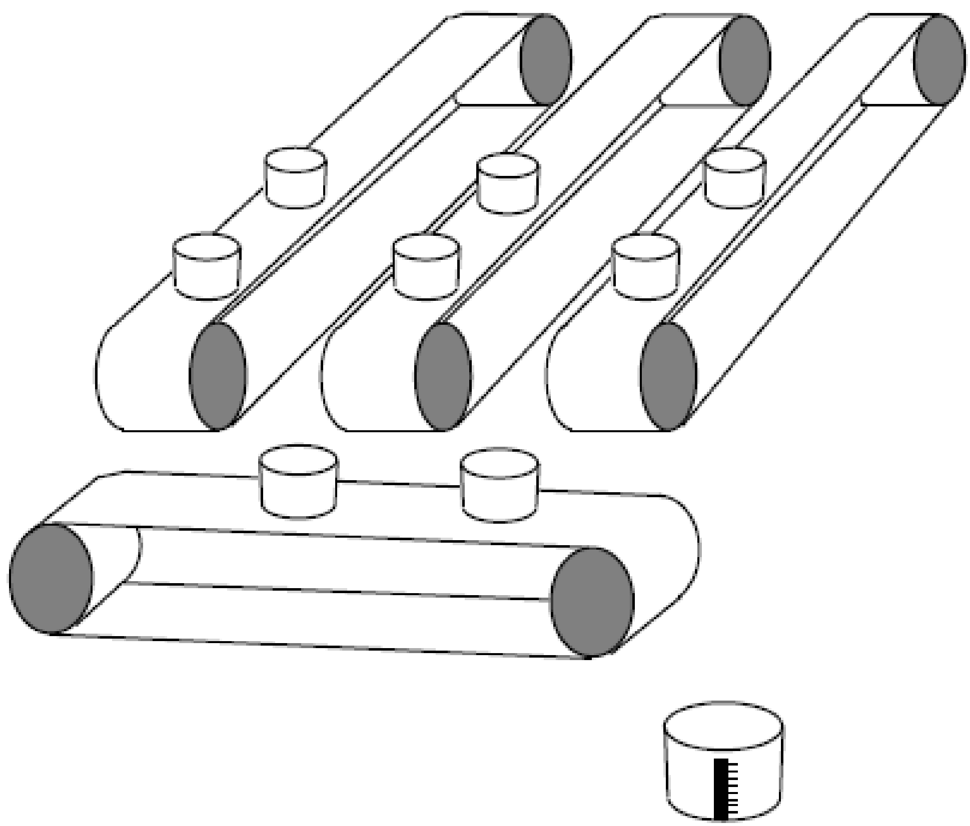


Leitura de CCDs

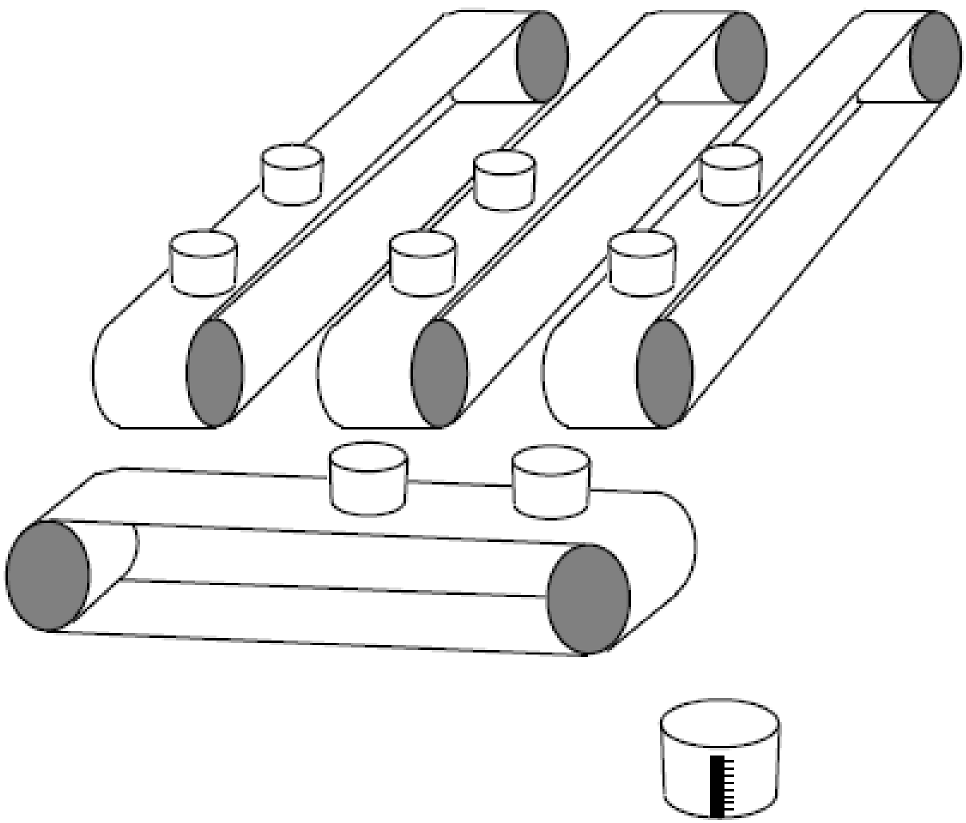
After each bucket has been measured, the measuring cylinder is emptied , ready for the next bucket load.



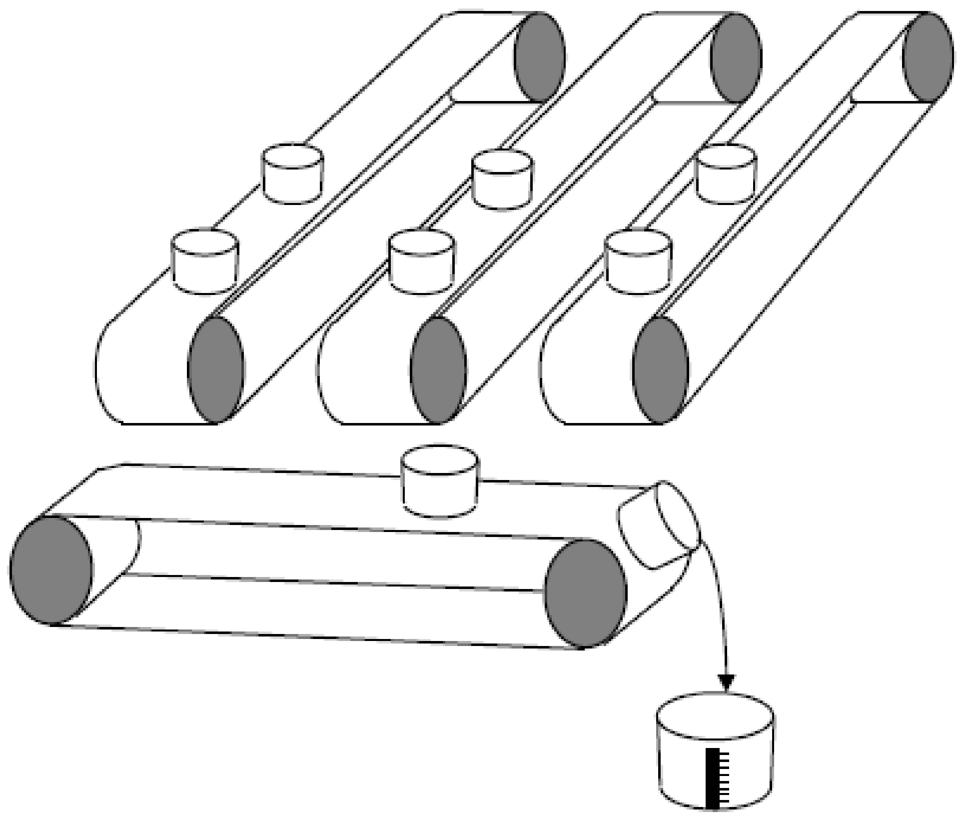
Leitura de CCDs



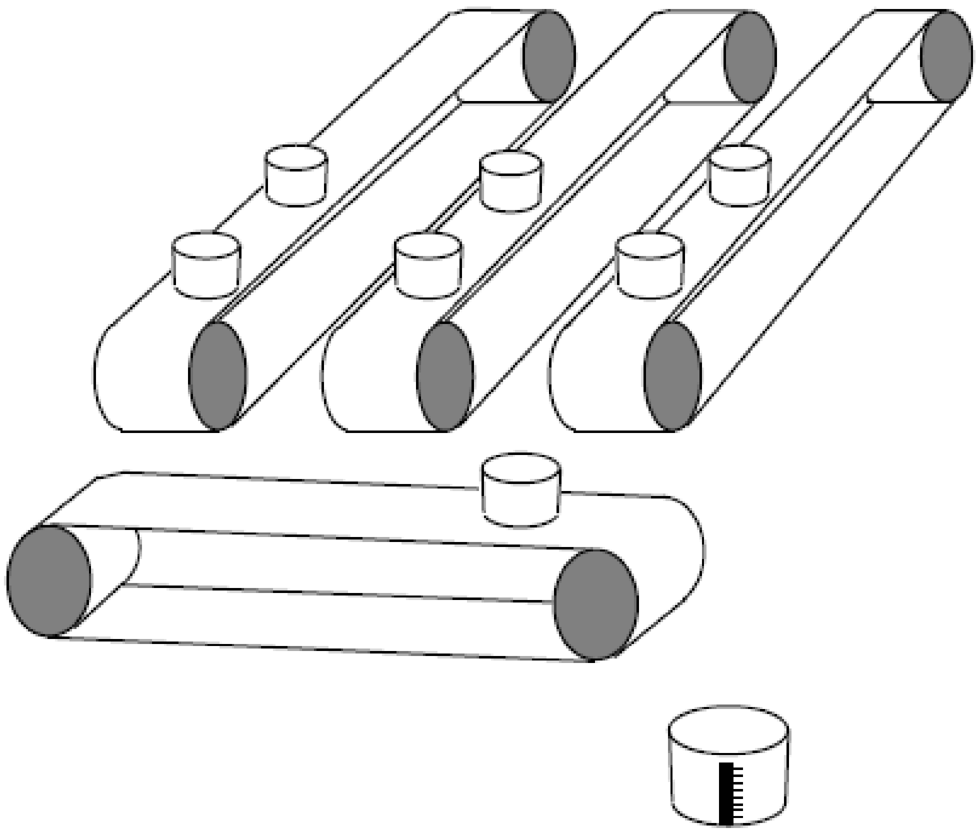
Leitura de CCDs



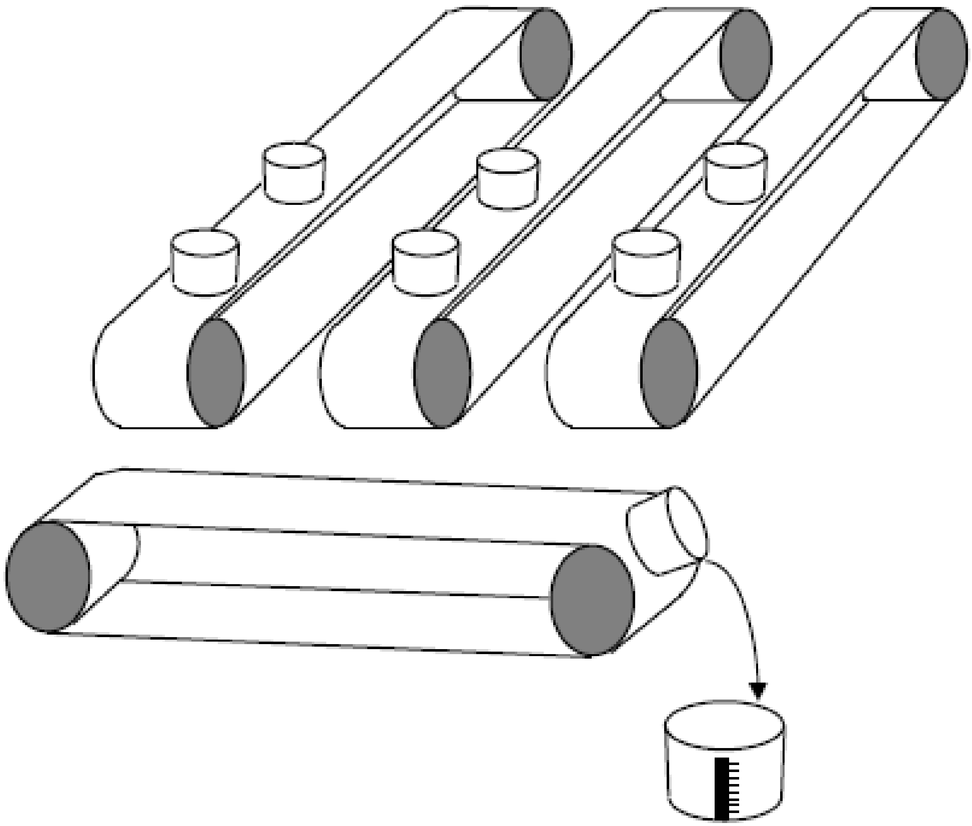
Leitura de CCDs



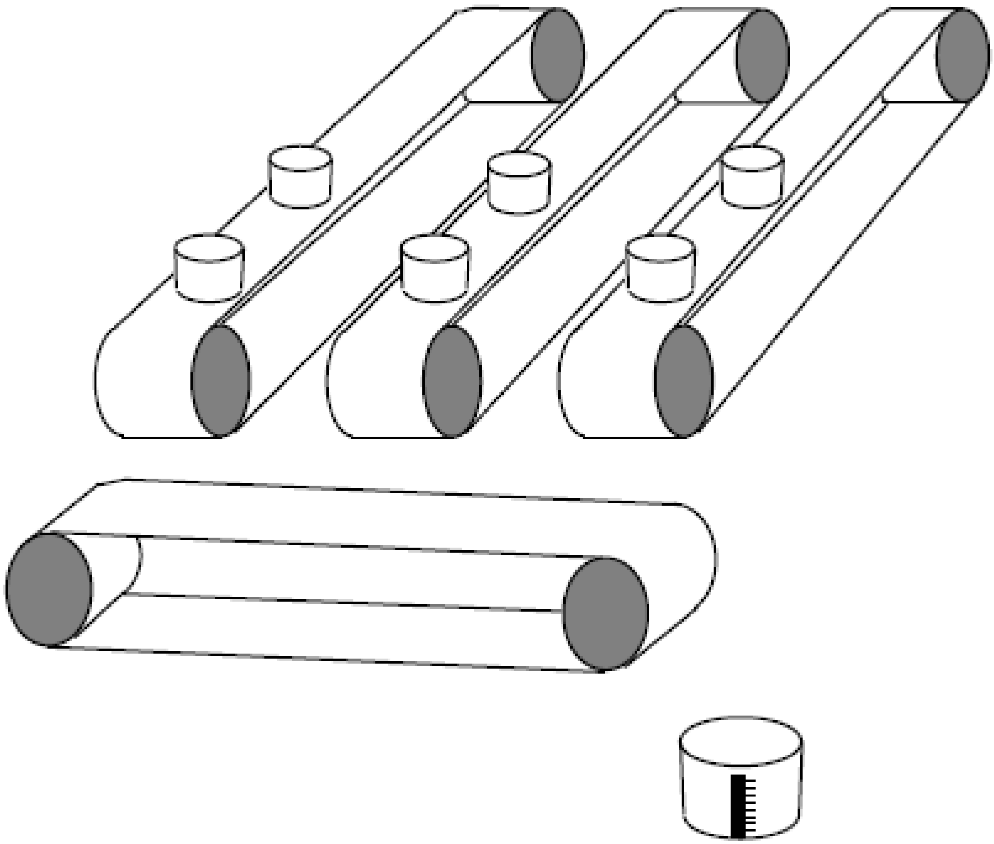
Leitura de CCDs



Leitura de CCDs

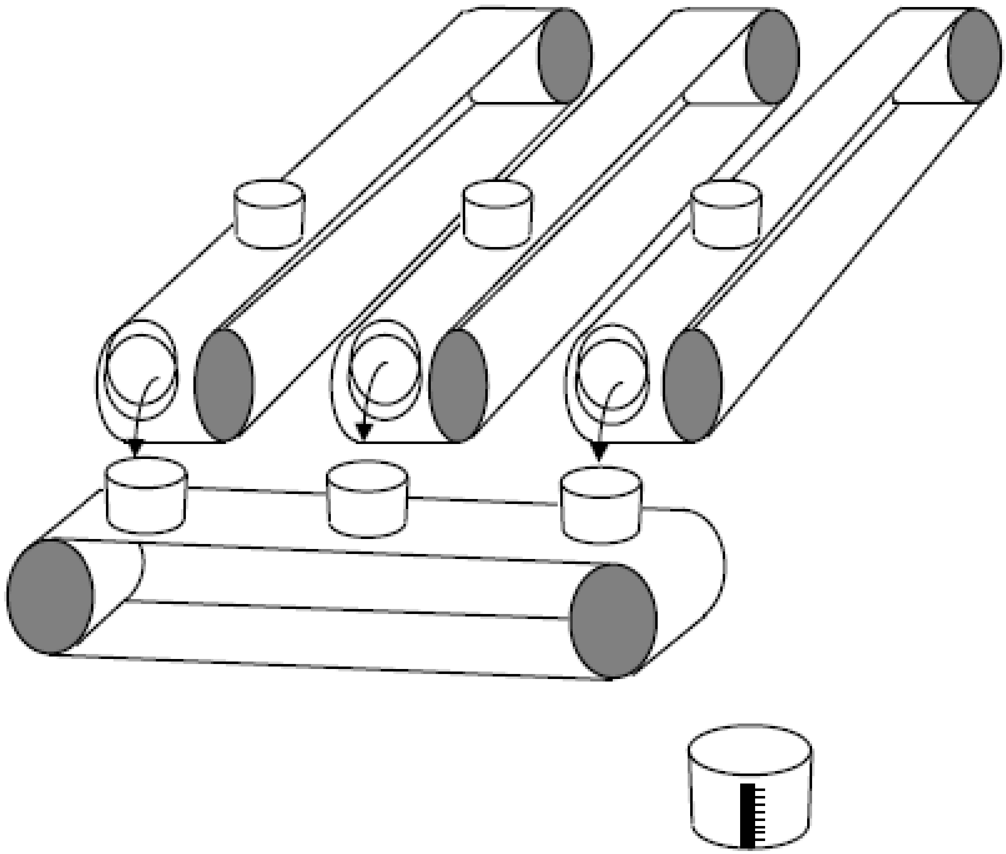


Leitura de CCDs

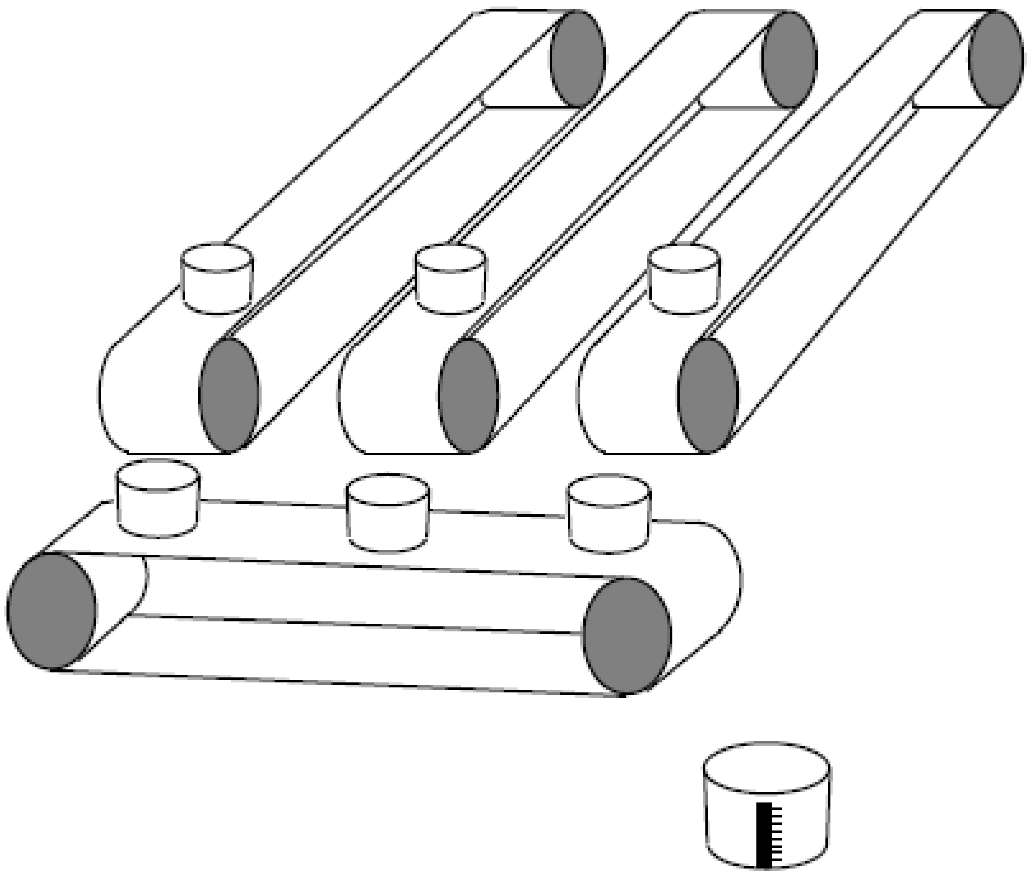


Leitura de CCDs

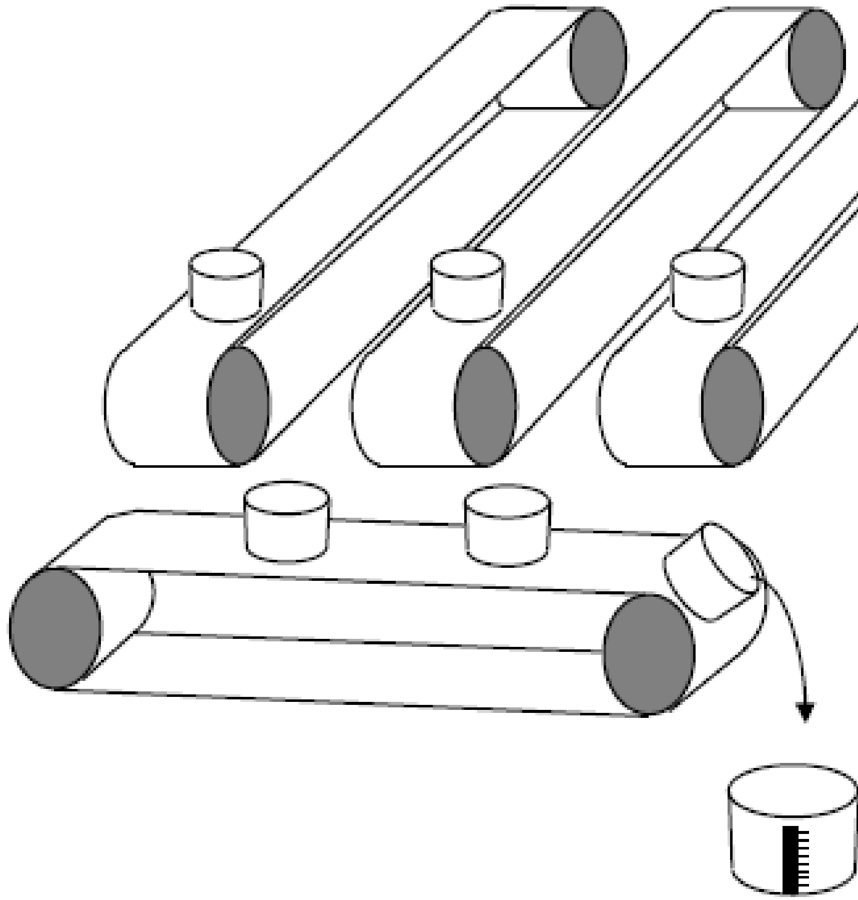
A new set of empty buckets is set up on the horizontal conveyor and the process is repeated.



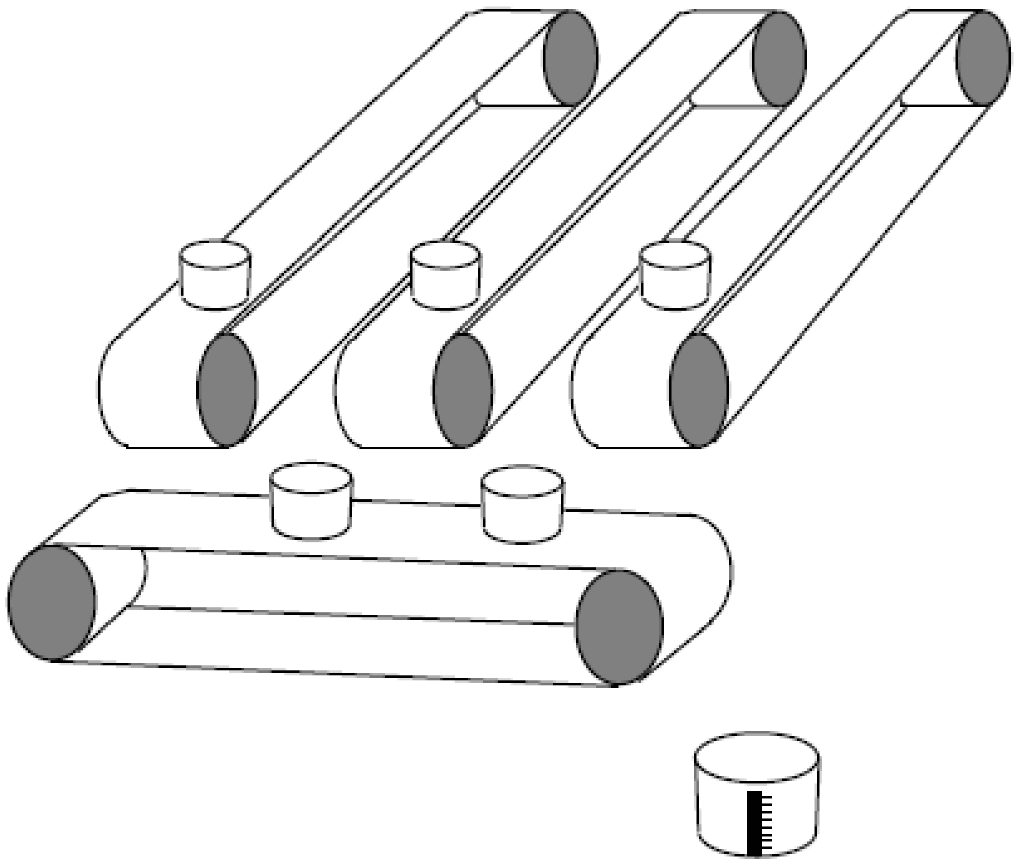
Leitura de CCDs



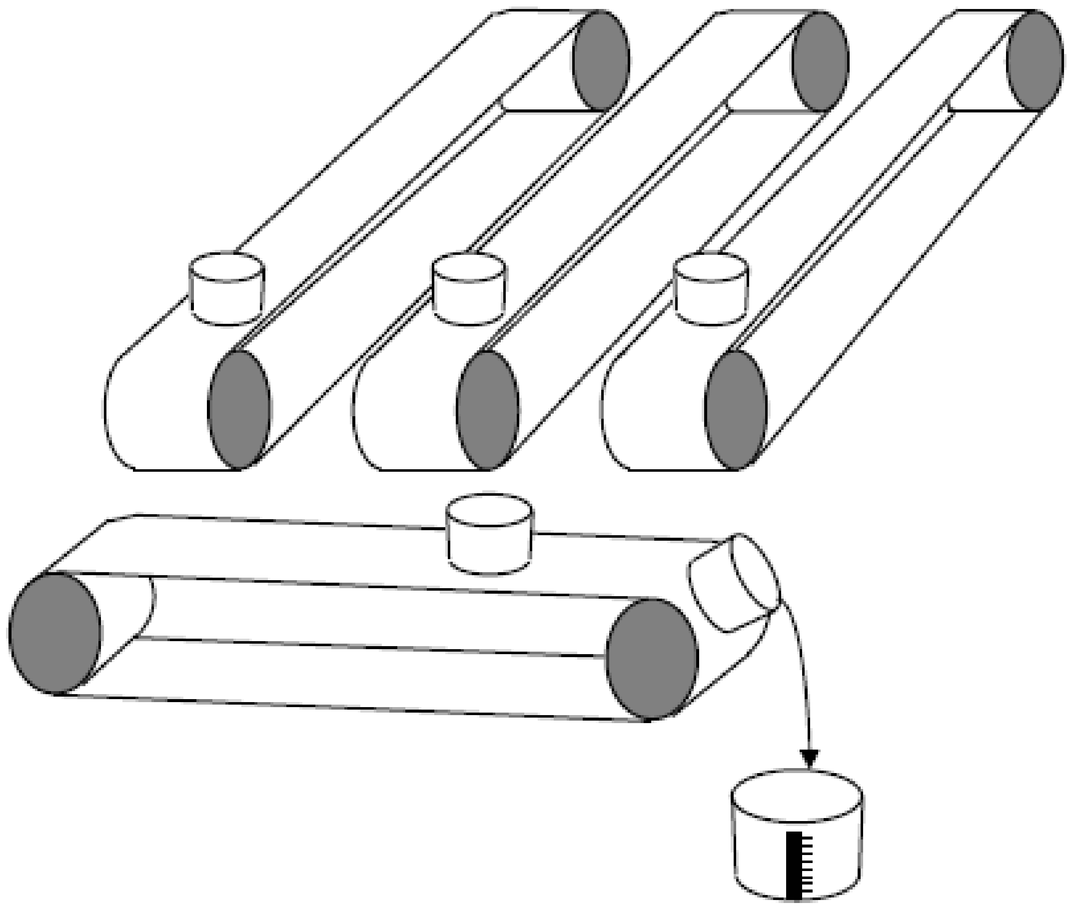
Leitura de CCDs



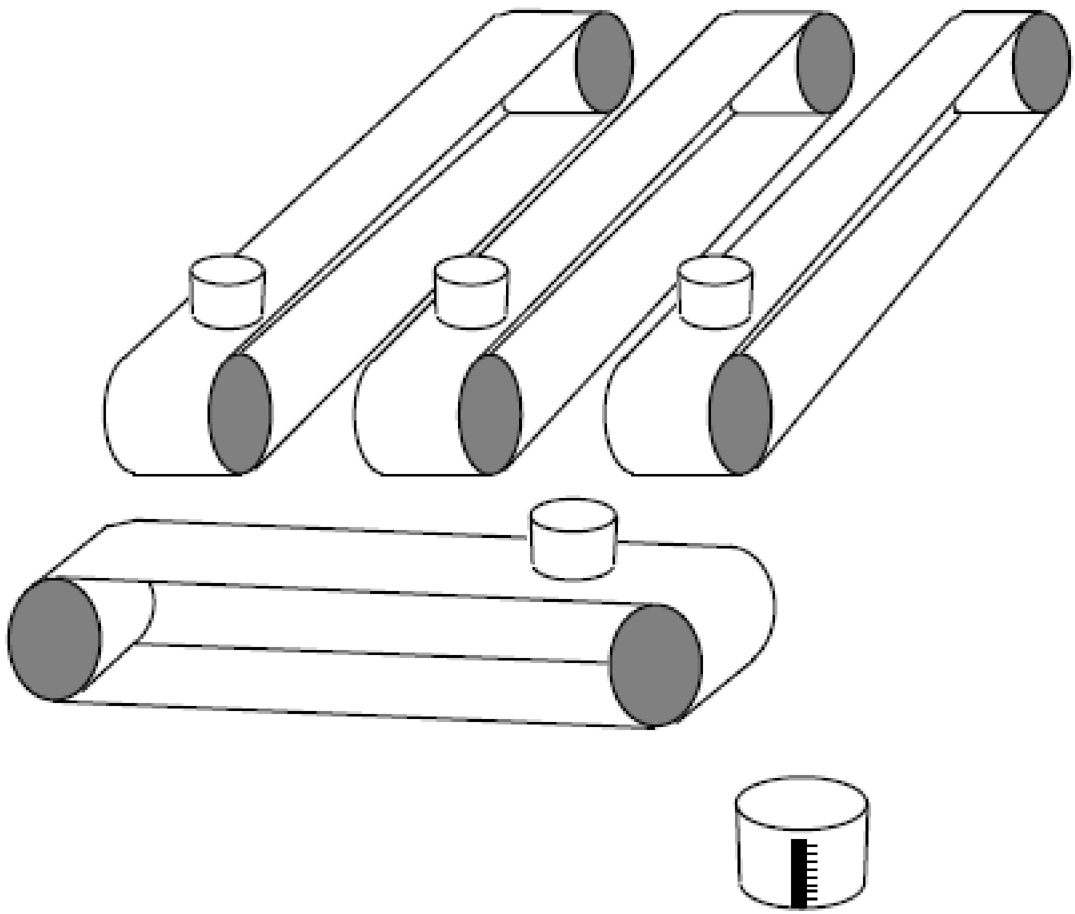
Leitura de CCDs



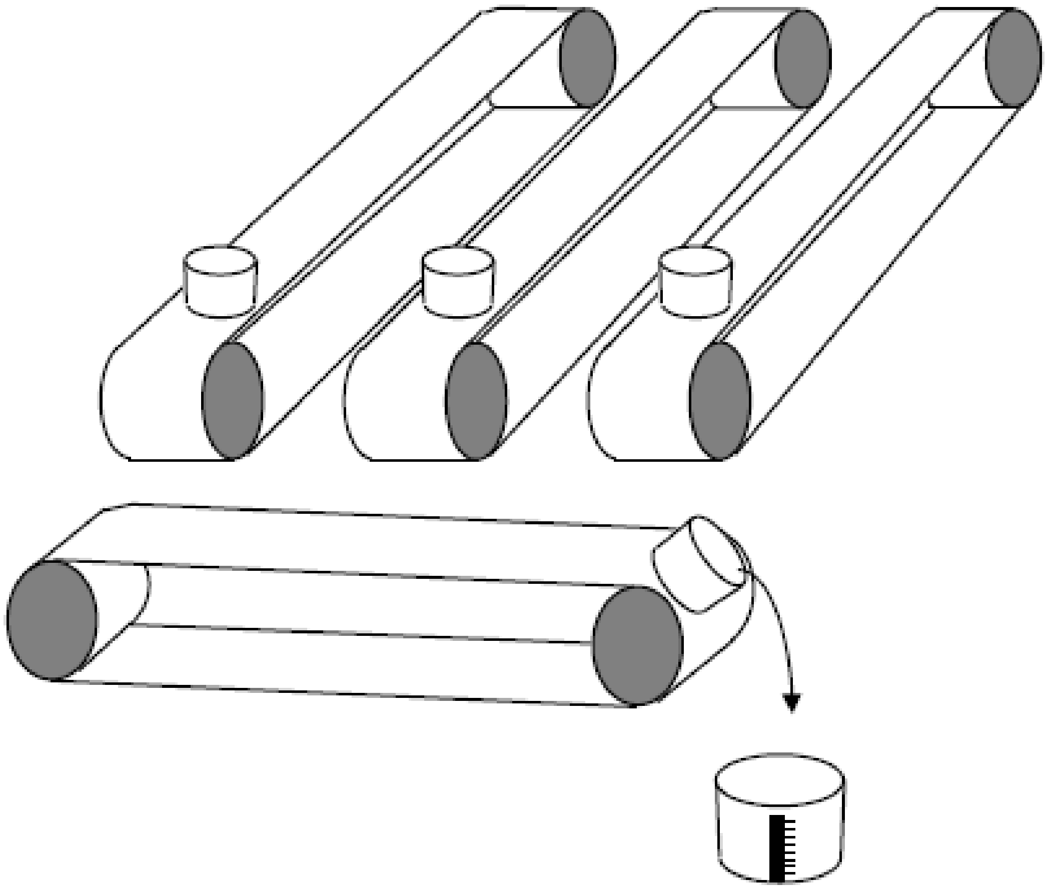
Leitura de CCDs



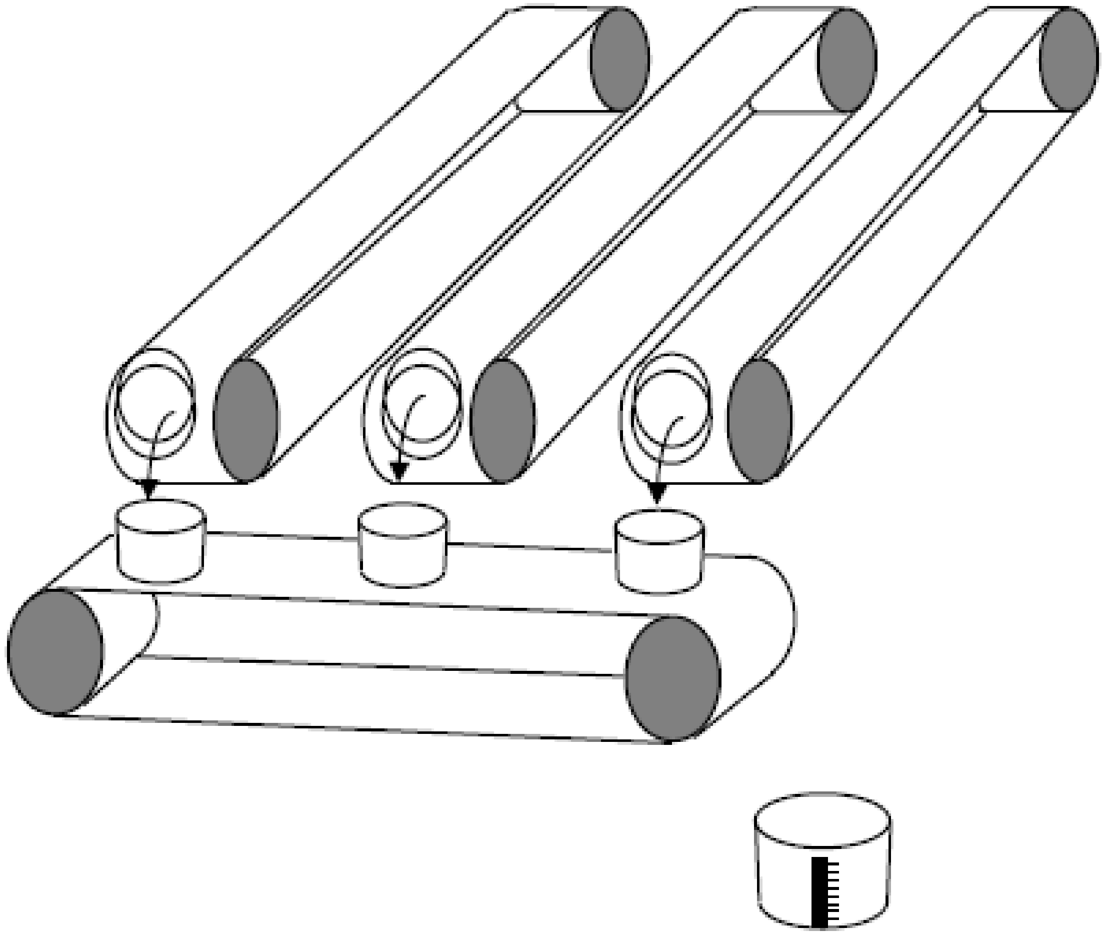
Leitura de CCDs



Leitura de CCDs

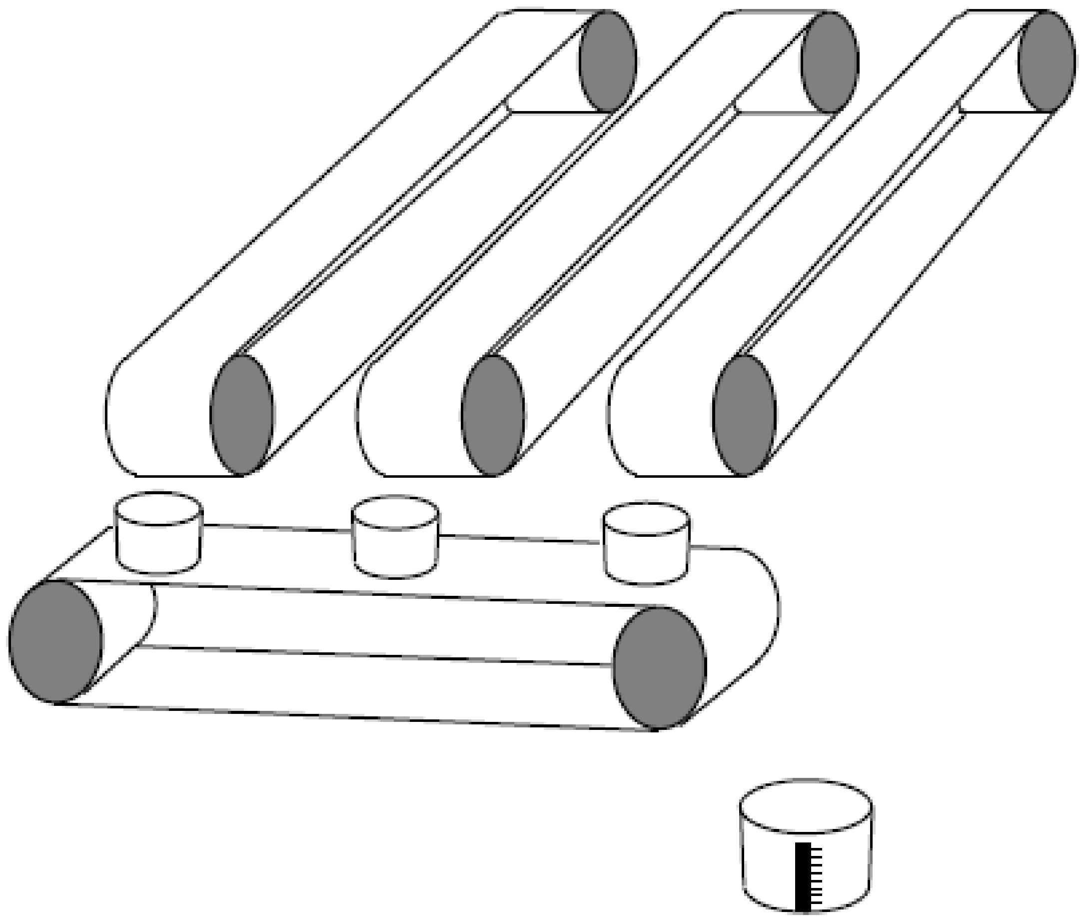


Leitura de CCDs

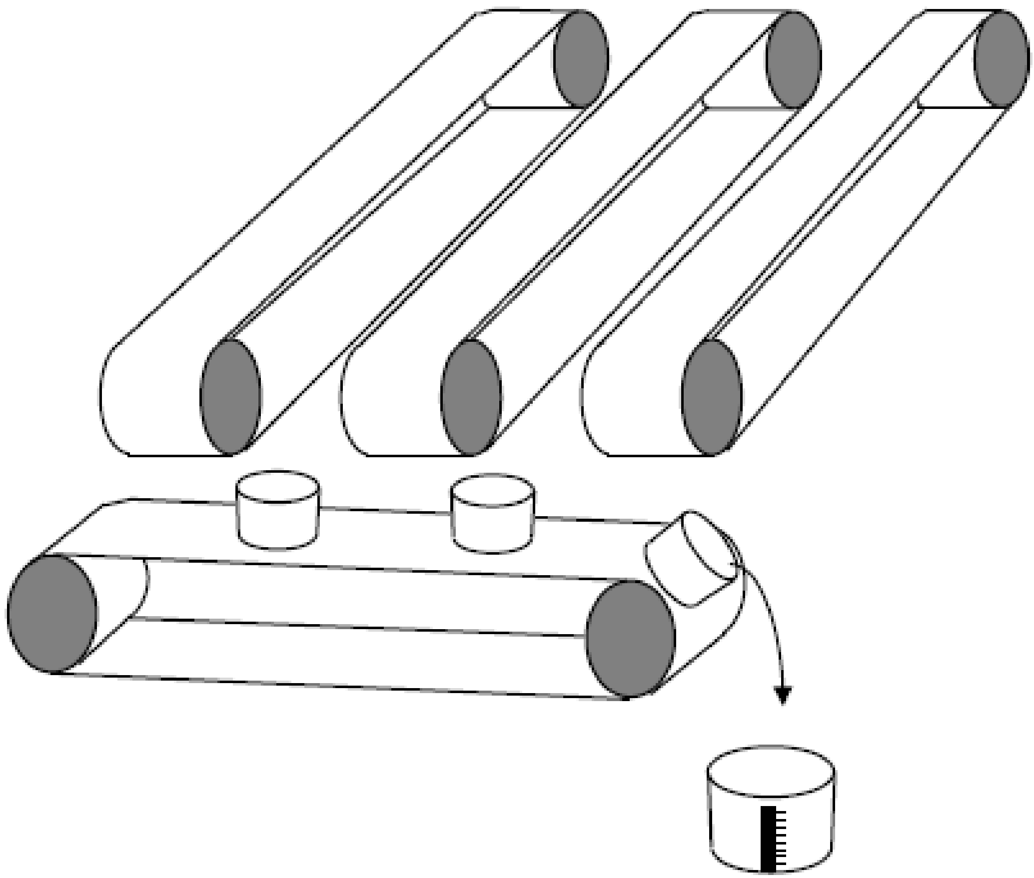


© Introduction to CCDs

Leitura de CCDs



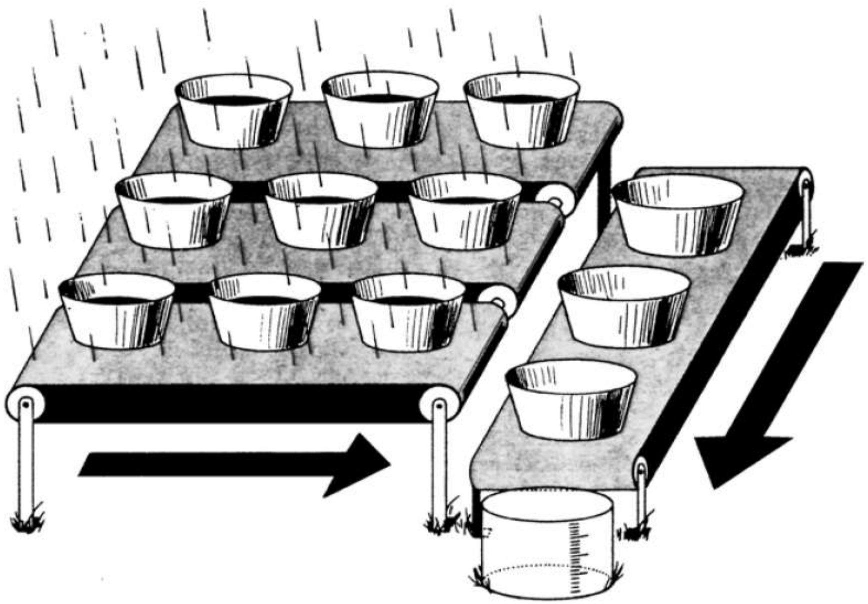
Leitura de CCDs



Transfer efficiency

- Early values about 0,999 (99,9%).

For 200 transfers (100x100 array) :



$$100 \text{ x } 0.999^{200} = 81\%$$

- Modern values ~ 0,999 999

CCDs: tamanho$

- Tipicamente 256x256, 512x512 pixeis, 1024 x 1024, 2048x2048, 4096 x 4096
- **Um dos maiores é o CCD231-C6 da E2V:**

6144 x 6144 pixeis

The pixels are 15µm in size

Tamanho total: 92.16 mm x 92.40 mm

CCD Heritage : Ground-based Telescopes

e2v scientific CCDs into most major worldwide telescopes

- Anglo Australian Observatory
- ANU Mount Stromlo Observatory (Australia)
- Canada France Hawaii Telescope (Hawaii)
- European Southern Observatory (Chile)
- Gemini Telescopes (Hawaii & Chile)
- Gran Telescopio Canarias (La Palma)
- Isaac Newton Group (La Palma)
- IUCCA (India)
- Keck Telescopes (Hawaii)
- LAMOST (China)
- Large Binocular Telescope (USA)
- Smithsonian Astrophysical Observatory/MMT (USA)
- Nordic Optical Telescope (La Palma)
- South African Large Telescope
- MODS on LBT
- SOAR (Chile)
- US Naval Observatory
- Warsaw University Observatory
- Developing sensors for LSST

CCD Heritage : Large Area Thinned

We have extensive experience in the design and manufacture of large area back illuminated CCDS :

CCD 42-90 :	**13.5µm pixel, 2k x 4.5k**	: General astronomy	>400 of these two types supplied
CCD44-82 :	**15µm pixel, 2k x 4k**	: General astronomy	

CCD43-62 :	**15µm pixel, 4k x 2k**	: Hubble WFC3 + ACS flight spares
CCD74-50 :	**12µm pixel, 2k x 4k**	: Solar B/SOT/FPP/ Filtergraph.
CCD42-CO :	**13.5µm pixel, 2k x 6k**	: Eddington
CCD90-52 :	**27µm pixel, 2200 x 1044**	: Kepler
CCD91-72 :	**30µm x 10µm pixel, 1966 x 4500**	: GAIA ASTRO AF
CCD203-82 :	**12µm pixel 4k x 4k**	: SDO : HMI / AIA & LAMOST
CCD231-84 :	**15µm pixel 4k x 4k**	: General astronomy

And now the very large area

CCD231- 68 :	**15µm pixel 8k x 3k**	LBT **M**ulti-**O**bject **D**ouble **S**pectrograph
CCD231- C6 :	**15µm pixel 6k x 6k**	Next generation astronomy imager
CCD290- 99 :	**10µm pixel 9k x 9k**	Next generation astronomy imager

Discovery Channel Telescope

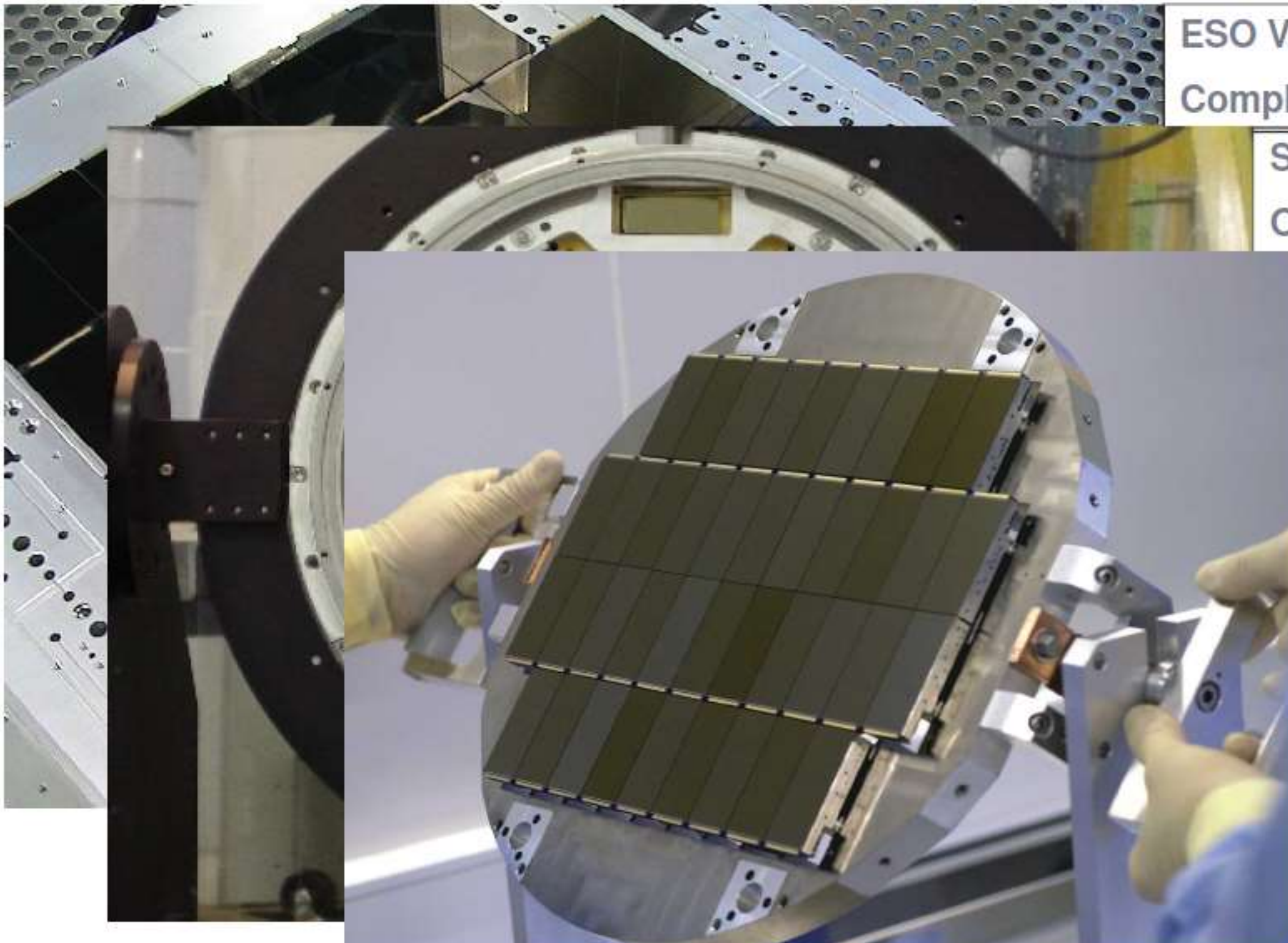
http://www.lowell.edu/techSpecs/LMI/LMI.html

LMI (Large Monolithic Imager) of Discovery Channel Telescope (4,3m) at Lowell Observatory

NGC 891 is an edge-on spiral galaxy, located about 10 Mpc (32 million light-years) away. The exposure was unguided and consist of ten 1-min exposures in B, five 1-minute exposures in V, and six 1-minute exposures in R. This was the ``first-light" image obtained with LMI obtained on September 12, 2012. **The field of view shown is 11.7 arcminutes on a side.**

Total field of view of CCD is 12,5’ x 12,5’

Ground-based CCD mosaic
CCD44-82 & CCD42-90



ESO VST Omegacam

Completed in lab.- 2005

SAO MMT Megacam

On telescope- 2005

CFHT Megacam

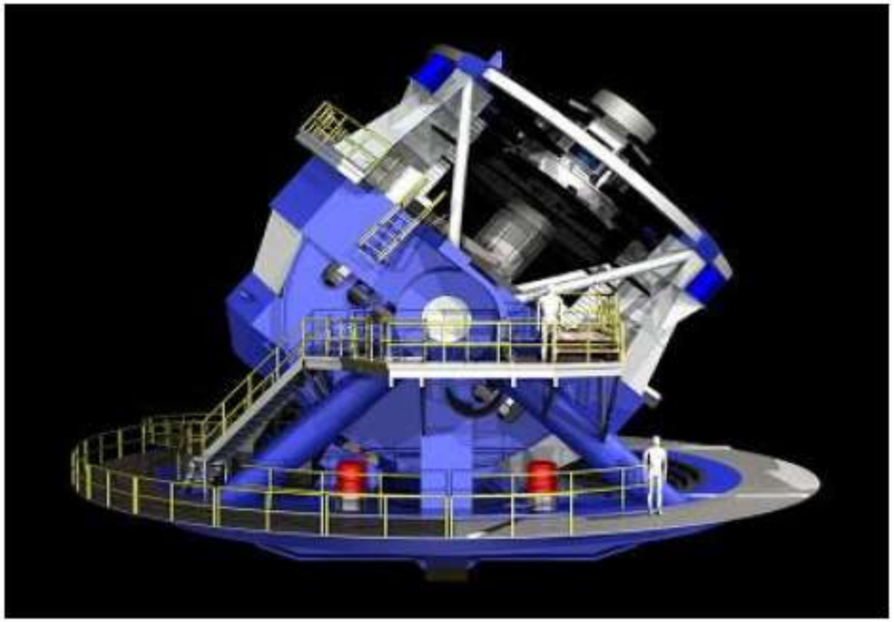
Operational- April 2003

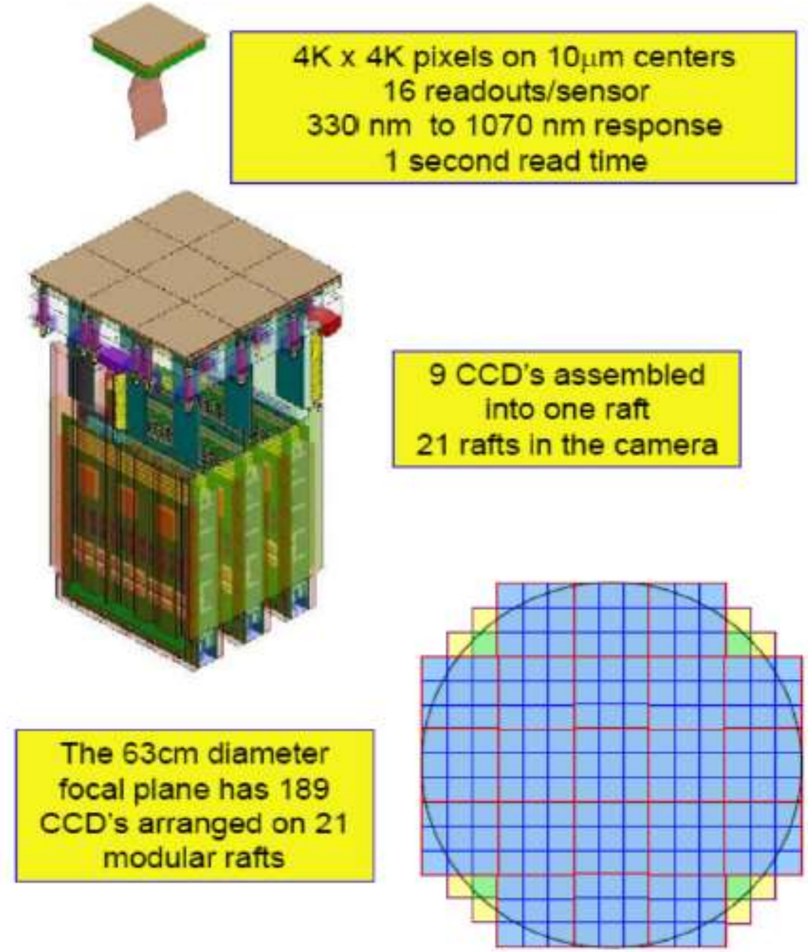
Kepler

Image supplied courtesy of Ball Aerospace

e2v supplied the CCDs for the Kepler instrument, which will greatly extend the search for extra-terrestrial planets

LSST





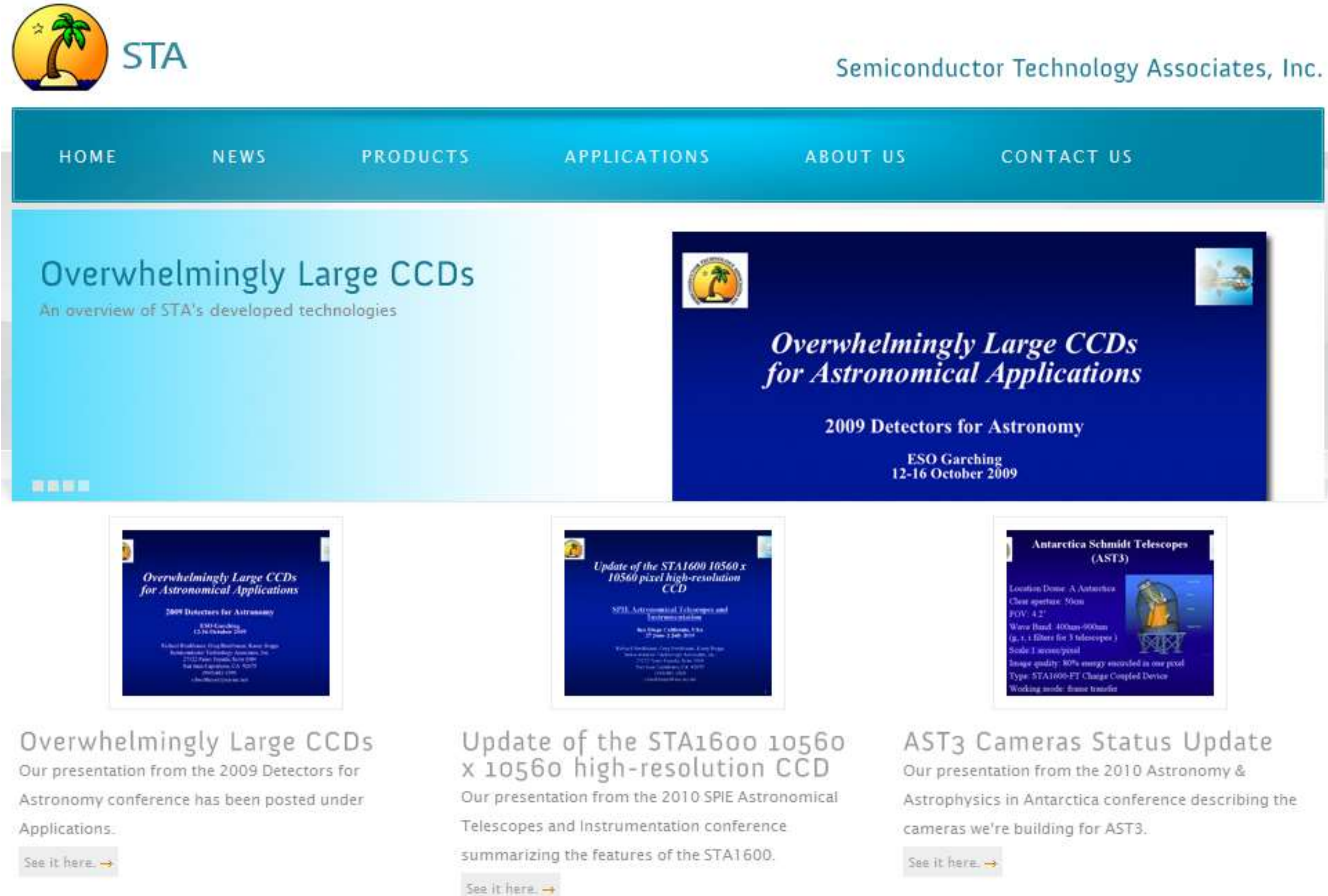
Acknowledgements to LSST

From AAS Jan 2008

8-m telescope
6-band (0.3-1.1 micron) wide-field deep astronomical survey of over 20,000 square degrees
Each patch of sky will be visited about 1000 times in ten years.
3200 Megapixels
9.6 square degree field of view
30 terabytes por noite

STA also produces huge chips

http://www.sta-inc.net/



STA1600

http://www.sta-inc.net/product-1/

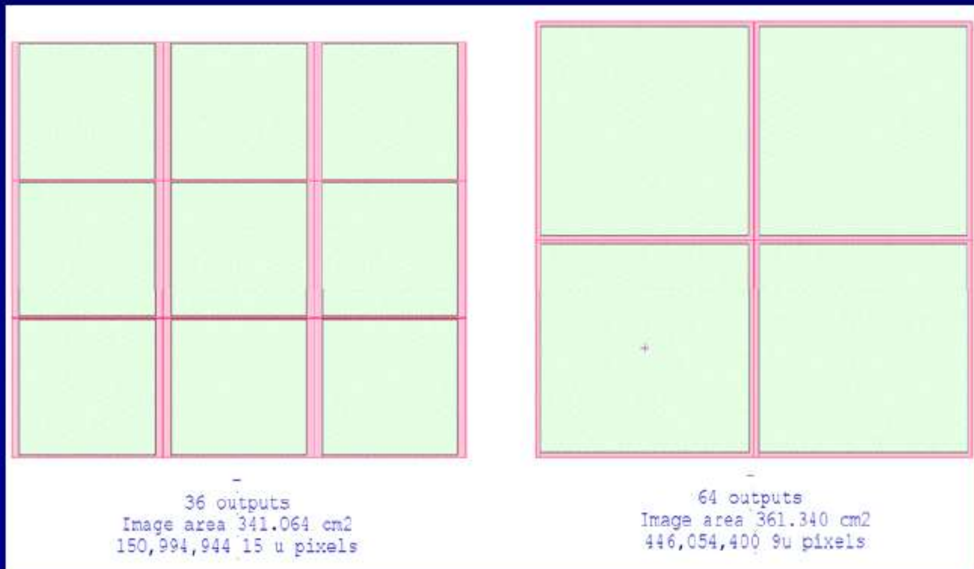
- 10560 x 10560
- 9 um pixel CCD
- 95.2 × 95.1 mm

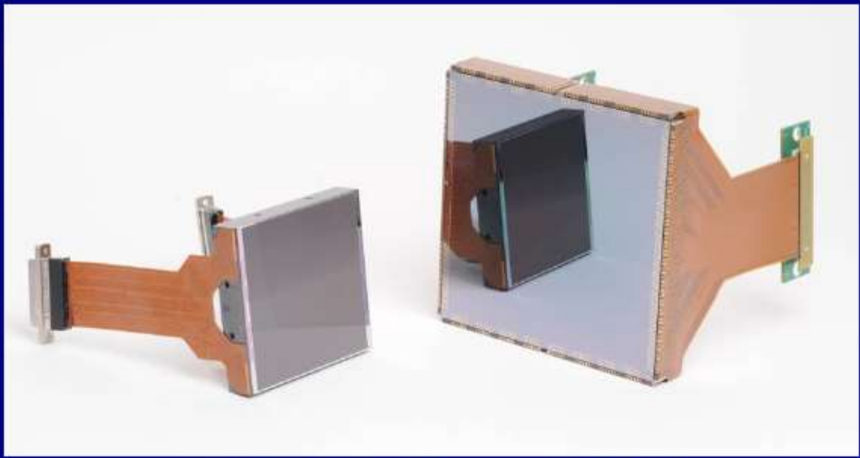
USNO Robotic Astrometric Telescope URAT

- 8 inch Refracting Telescope for Astrometry
- Upgrade initiated to a 2x2 array by Dr Norbert Zacharias for an all sky survey - URAT
- STA is providing complete system including
  - Dewar – Window – Bonn Shutter
  - Four BI STA1600B CCDs – Three STA 3000 Guiders
  - Five Aura cameras with software
  - Telescope robotic control software

http://www.sta-inc.net/wp-content/uploads/2010/08/Overwhelmingly-Large-CCDs-for-Astronomy.pdf

Large Focal Plane Efficiency





E2V CCD231 adjacent to STA1600

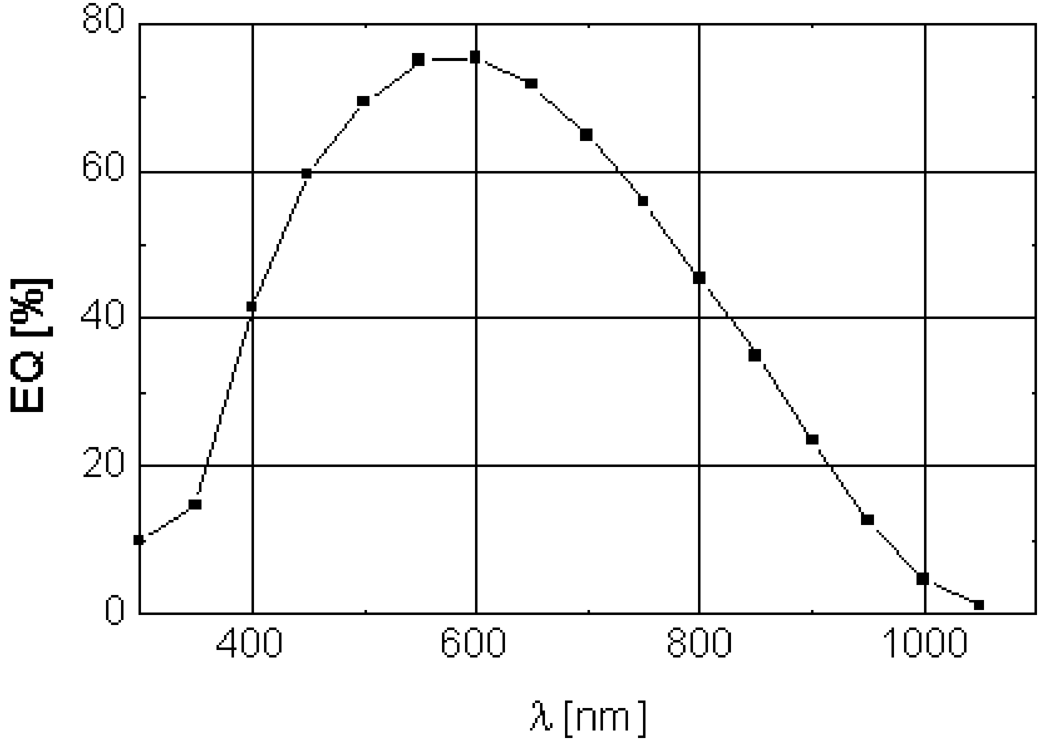
- Four 10ks provide more active image area than nine 4k imagers
- 91% Active area for 4k imager
- 95% Active area for 10k imager

http://www.sta-inc.net/wp-content/uploads/2010/08/Overwhelmingly-Large-CCDs-for-Astronomy.pdf

Quantum efficiency (Q.E.)

$$Q.E. = \frac{\text{número médio de fótons detectados}}{\text{número médio de fótons incidentes no detector}}$$

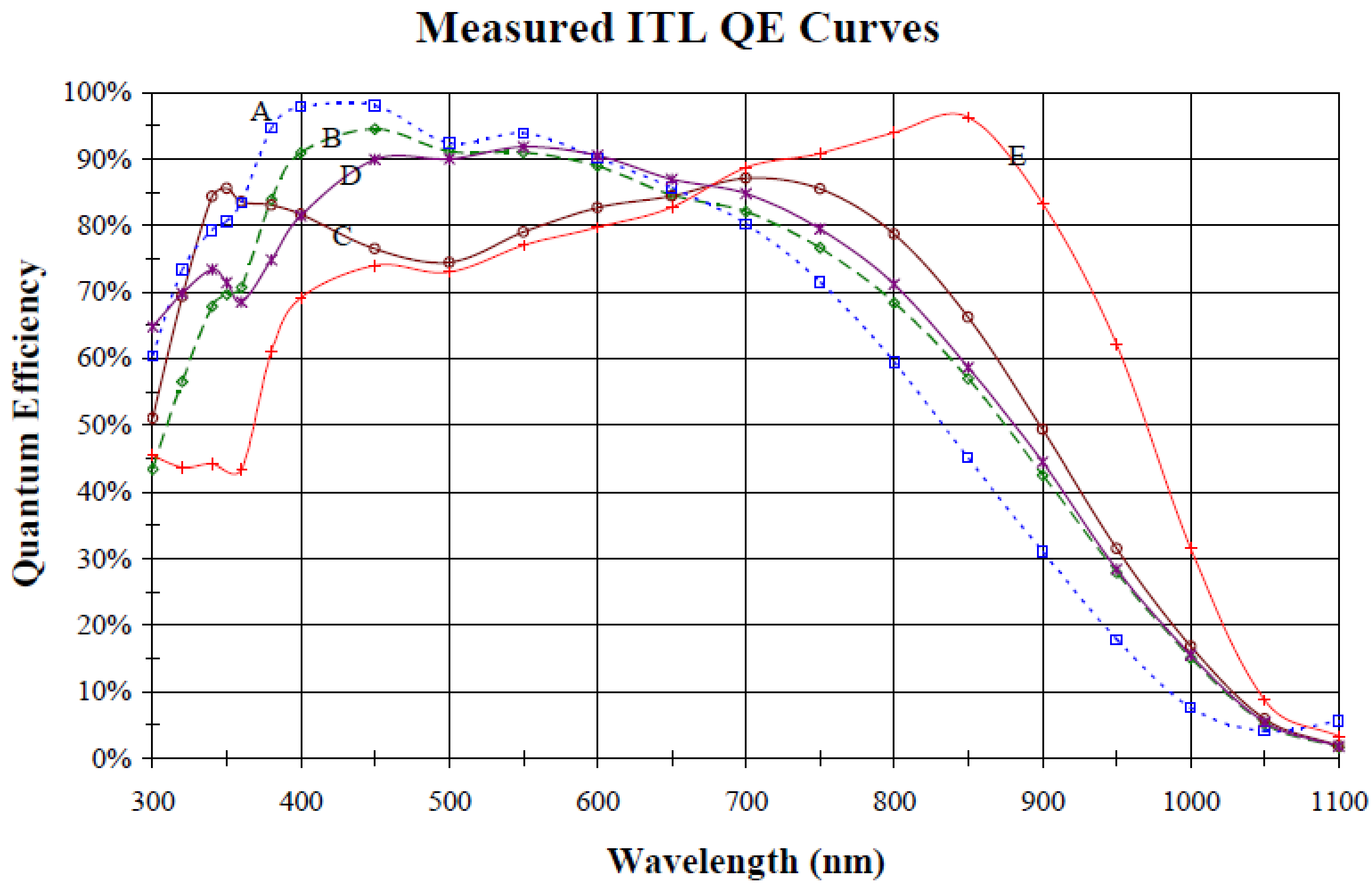
Eficiência Quântica - CCD 105 (OPD)



http://www.lna.br/opd/instrum/ccd/qefull_105_160.html

Quantum efficiency

For STA arrays



M. Lesser, University of Arizona Imaging Technology Laboratory

- A and B are blue optimized coatings.
- C and D are broadband. D is a new AR coating .
- E is a device with a red optimized coating.

http://www.sta-inc.net/wp-content/uploads/2010/08/Overwhelmingly-Large-CCDs-for-Astronomy.pdf

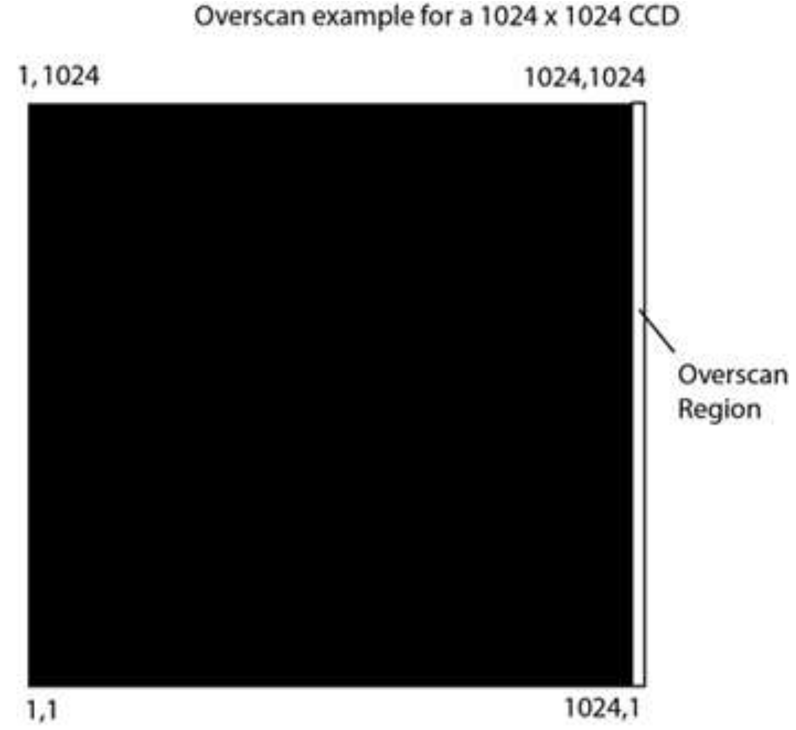
Bias

- A bias frame is an exposure of zero duration taken with the camera shutter closed e todas as luzes desligadas!
- “Ponto zero” das contagens
- Obter **no mínimo** 10 bias e fazer mediana
- Problema: variações durante a missão?

Bias e overscan

- Valor médio do bias tb pode ser obtido do overscan do CCD
- Se esqueceu de obter bias: bias = median(overscan)
- Se o bias mudar:

bias = bias + median(overscan) - median(bias)



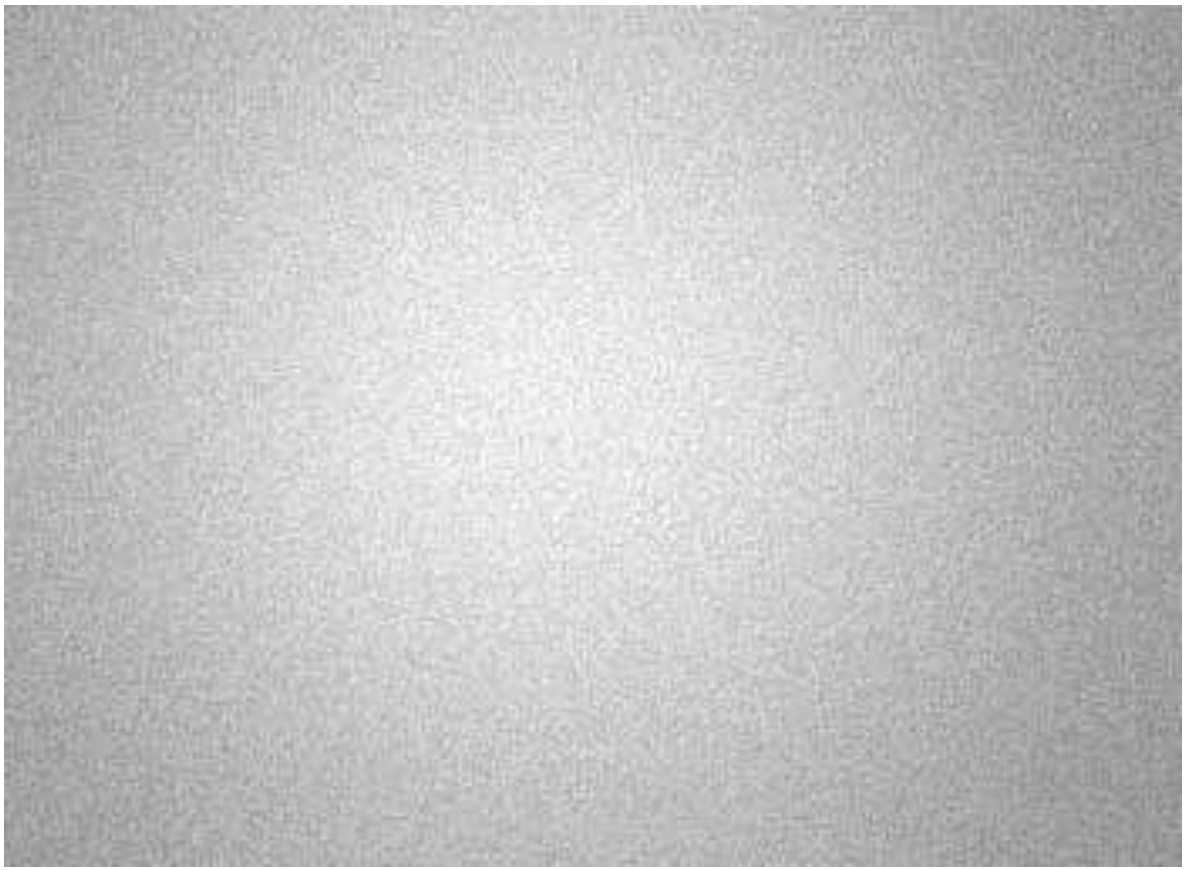
Flat

Imagem para corregir diferenças na sensibilidade do CCD e outros efeitos. Obter **no mínimo** 5-10 flats.

"dome" flat

1,6m do OPD
Março 2013

Flat

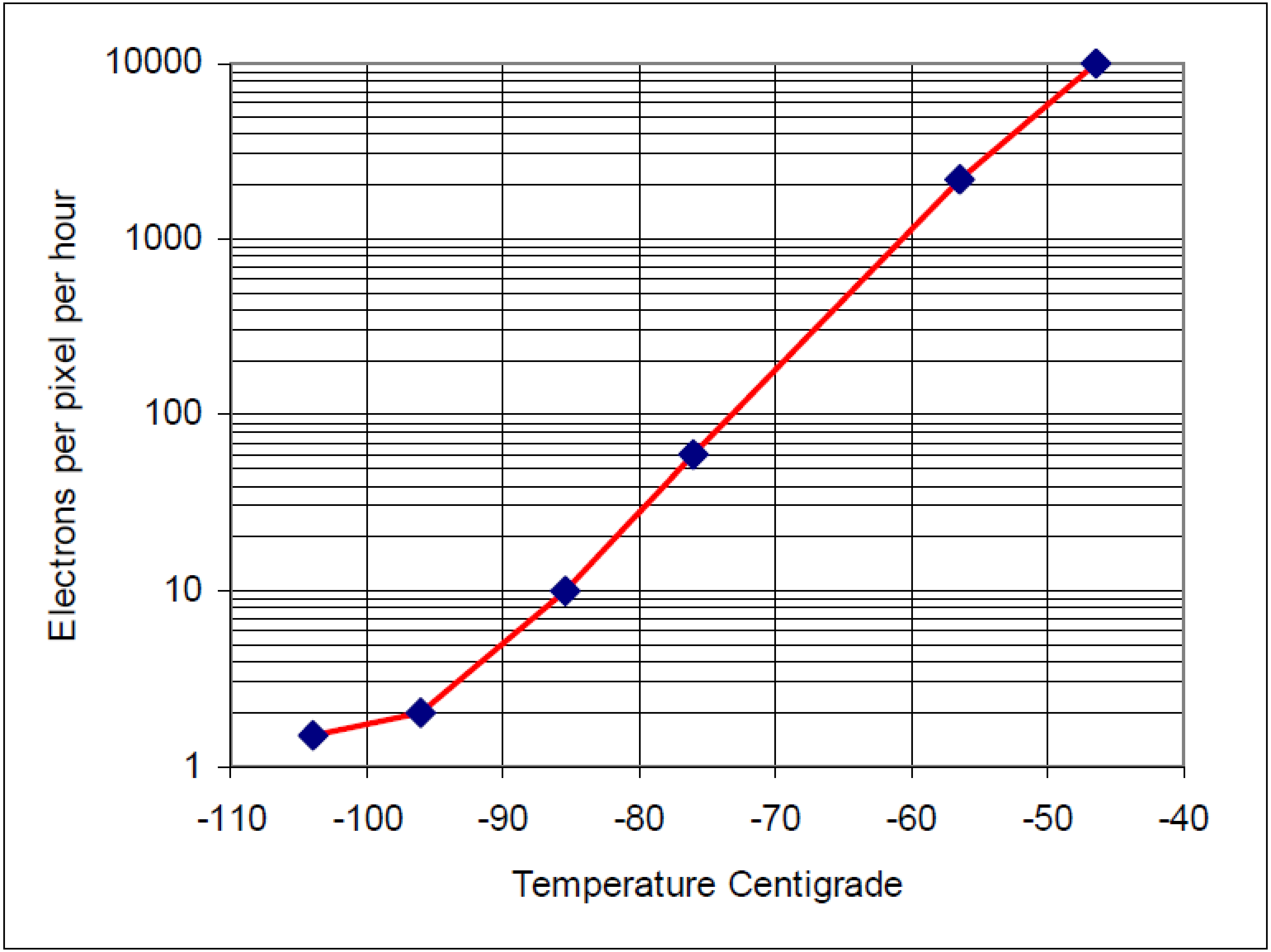


Dark (current)

- Dark current é devido às contagens aleatorias devido ao efeito térmico. É quase desprezível em CCDs resfriados com nitrogênio líquido
- Pode ser importante para objetos muito fracos
- Deve ser de exatamente o mesmo tempo de exposição do objeto, ou escalar com o tempo:

Dark/tempo = (Dark – bias)/tempo

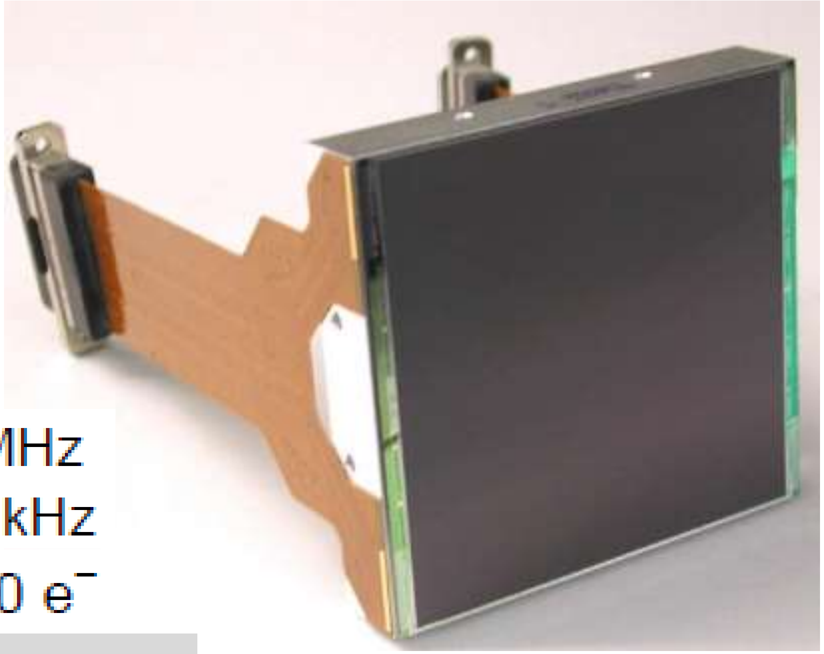
Dark current of a TEK1024 CCD



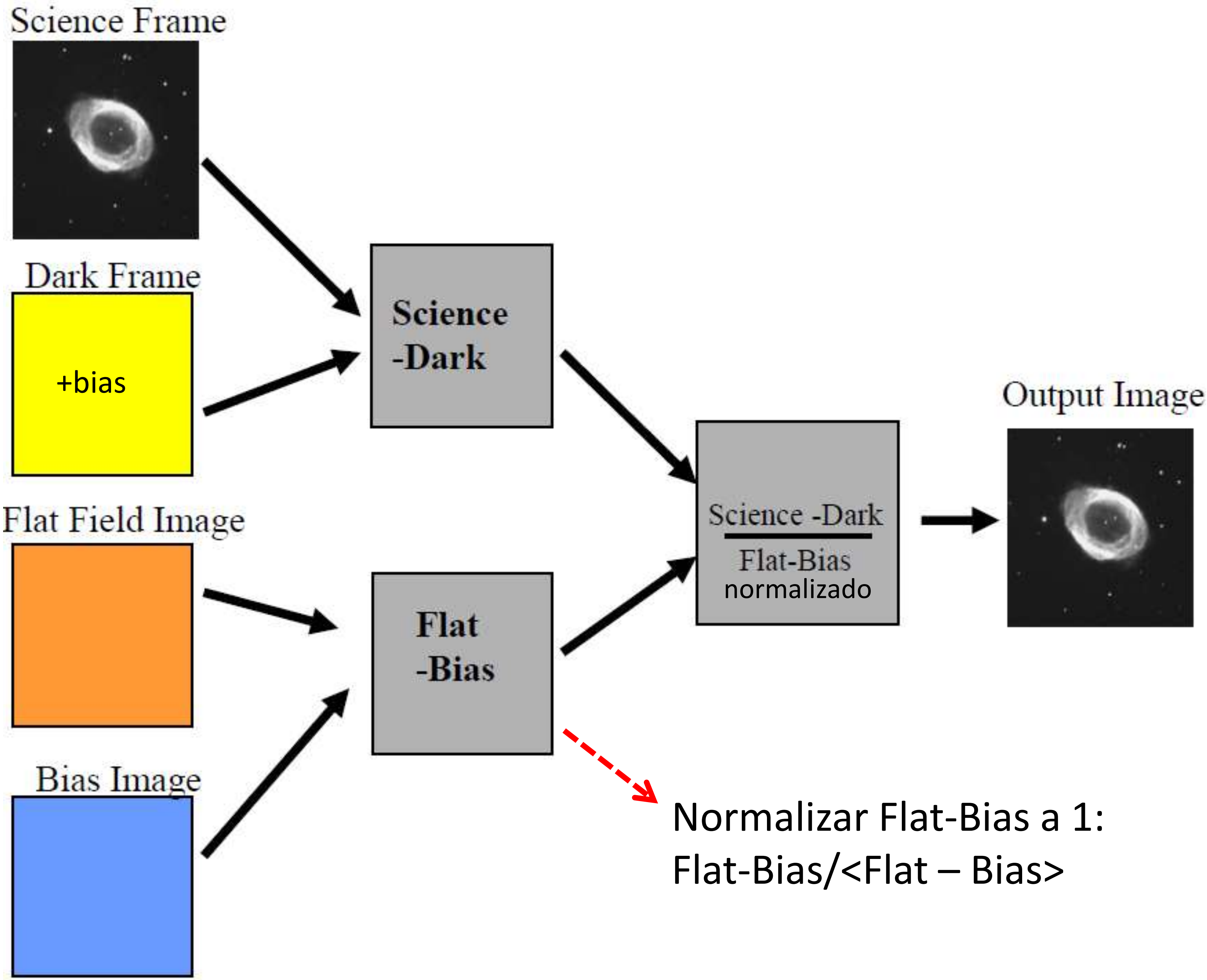
Outro exemplo: CCD 231-84 (e2v) 4096x4096 pixeis

SUMMARY PERFORMANCE (Typical)

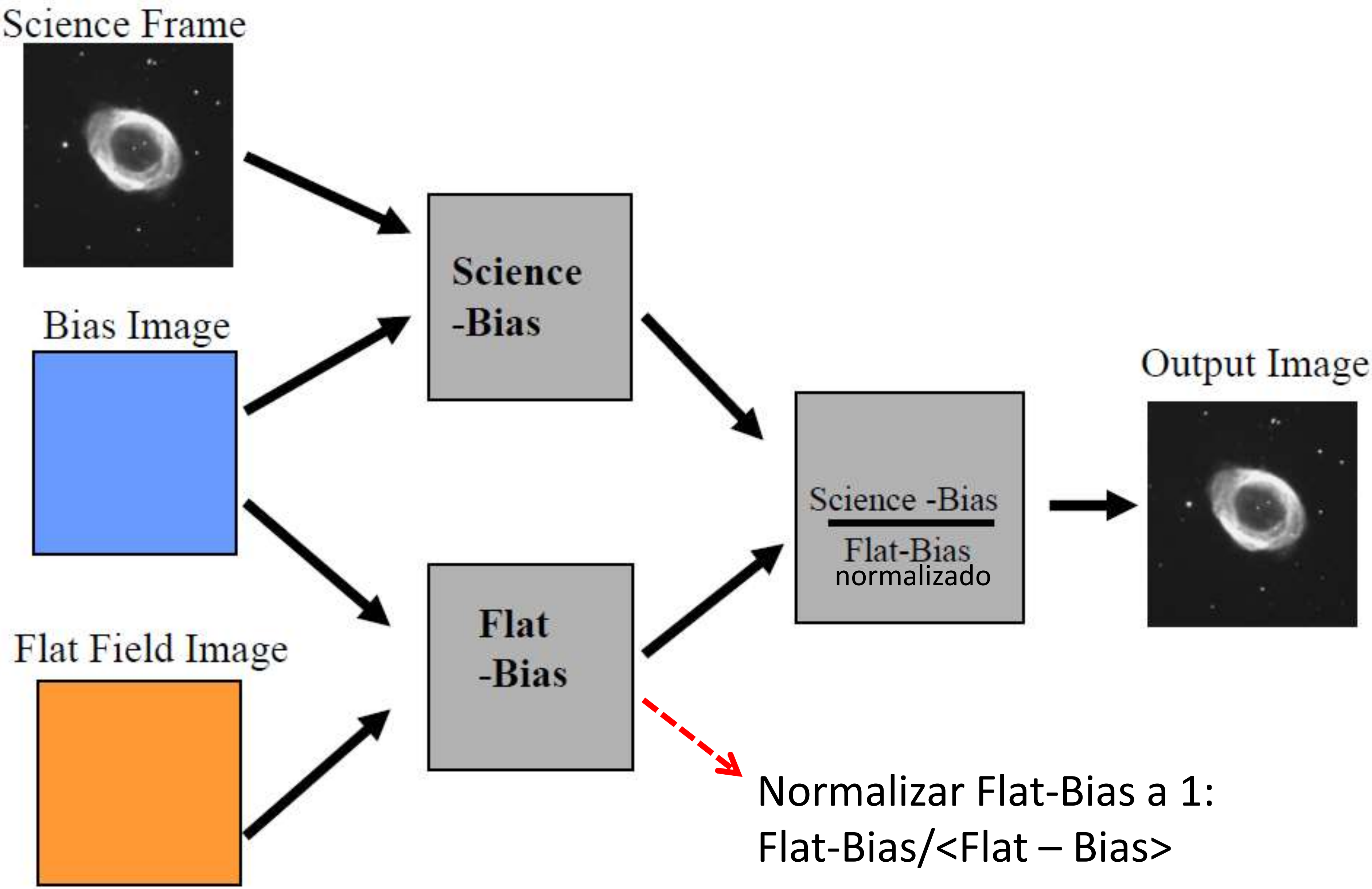
Number of pixels	4096(H) x 4112(V)
Pixel size	15 µm square
Image area	61.4 mm x 61.4 mm
Outputs	4
Flatness	<20 µm (peak to valley)
Readout noise	5 e⁻ at 1 MHz 2 e⁻ at 50 kHz
Charge storage (pixel full well)	350,000 e⁻
Dark signal	3 e⁻/pixel/hour (at –100 °C)
at 153 K	0.02 e⁻/pixel/hr



Charge transfer efficiency: 99.9995



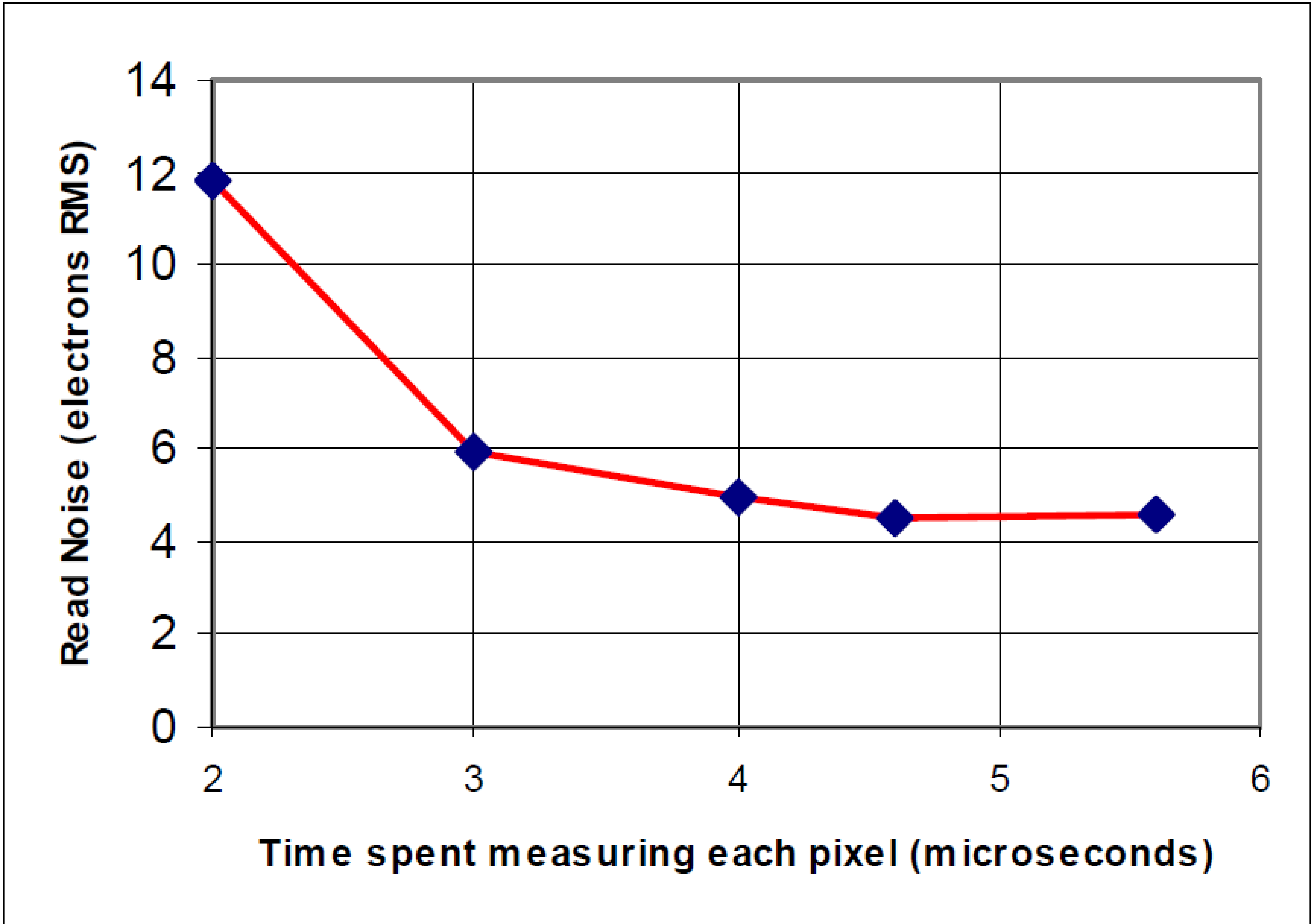
Science Frame
Dark Frame
+bias
Flat Field Image
Bias Image
Science
-Dark
Flat
-Bias
Science -Dark
Flat-Bias
normalizado
Output Image
Normalizar Flat-Bias a 1:
Flat-Bias/<Flat – Bias>



Normalizar Flat-Bias a 1:
Flat-Bias/<Flat – Bias>

Erro de leitura

noise and readout speed for an EEV4280 CCD



Noise in a CCD image

$$NOISE_{total} = \sqrt{(READ\ NOISE)^2 + (PHOTON\ NOISE)^2 + (DARK\ CURRENT)^2}$$

Per "frame"

Sqrt(e-)

Can be lowered cooling the detector

Linearidade

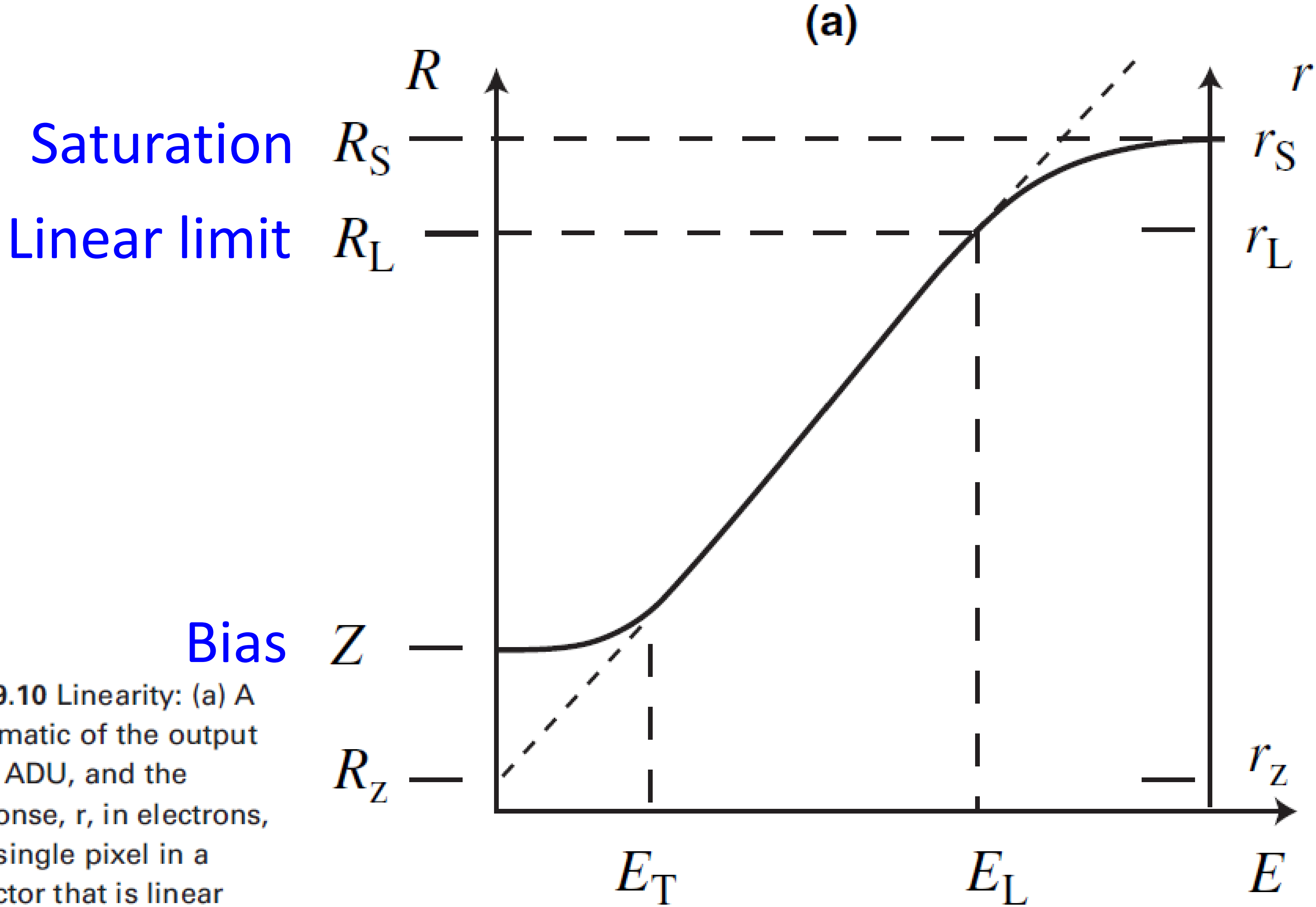


Fig. 9.10 Linearity: (a) A schematic of the output R, in ADU, and the response, r, in electrons, of a single pixel in a detector that is linear over a restricted input range. The sloped

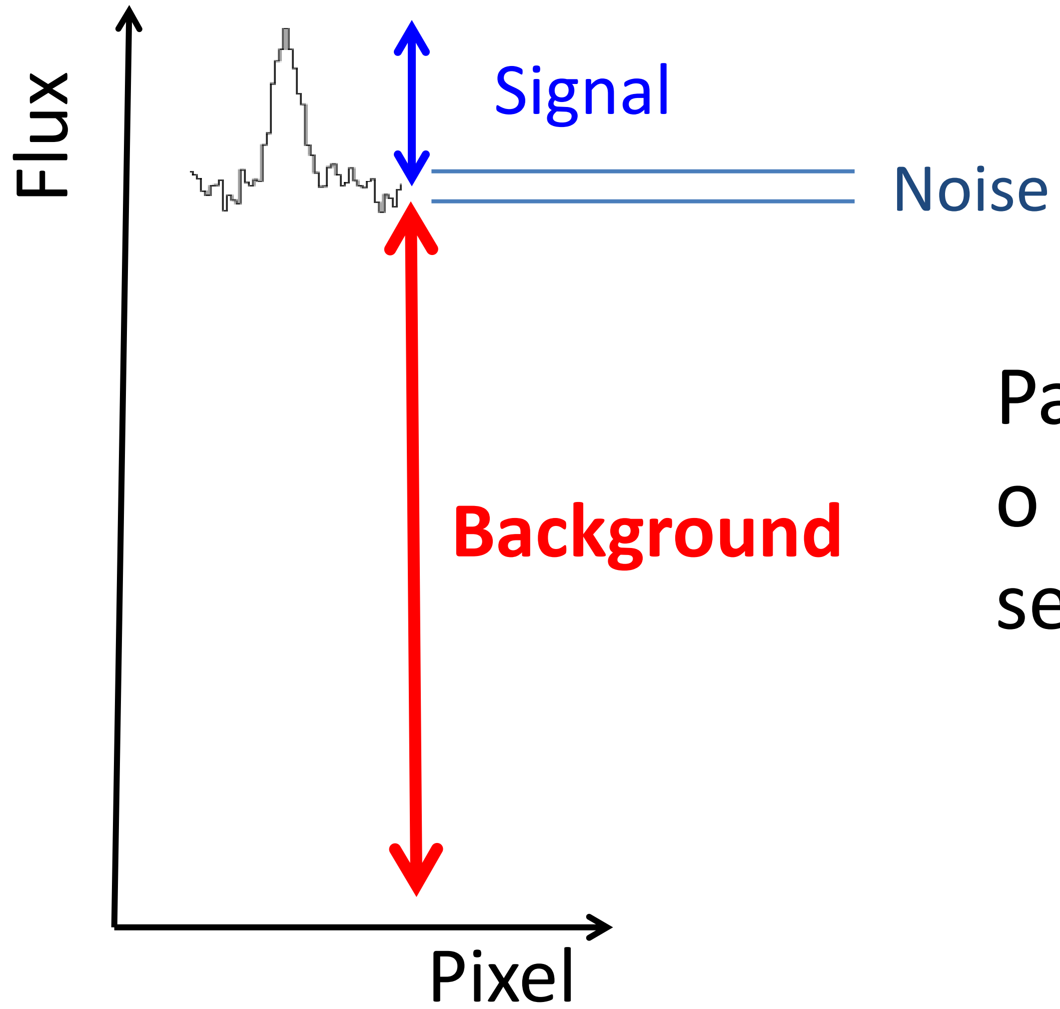
Contagens vs. e-: GAIN

- Gain is reported in terms of electrons/ADU (analog-to-digital unit)
- Gain = 8 means each “count” = 8 e-
- 8e-/ADU
- Em estatística (p.ex. photon noise) tem que ser usado o #e-, não o #contagens (ADU)

Exemplo: 5e-/ADU, então 200 contagens equivalem a 1000 e-

Signal, noise & background

É possível detetar um sinal mais fraco que o brilho do céu?



Para uma detecção, o sinal >> ruído, ou seja, S/N >> 1

Signal-to-noise ratio (S/N)

S/N = 2: tentative detection

S/N = 3: OK

S/N = 5: firm detection

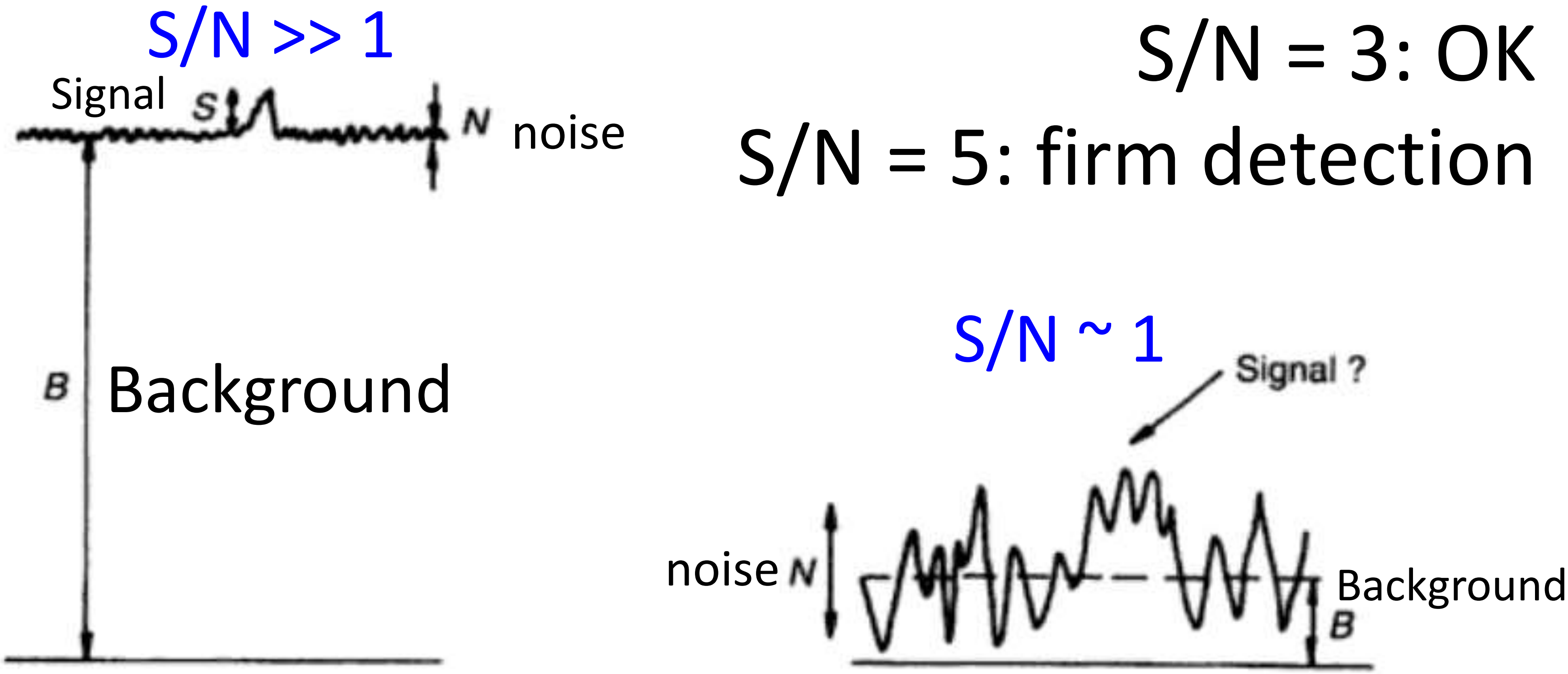
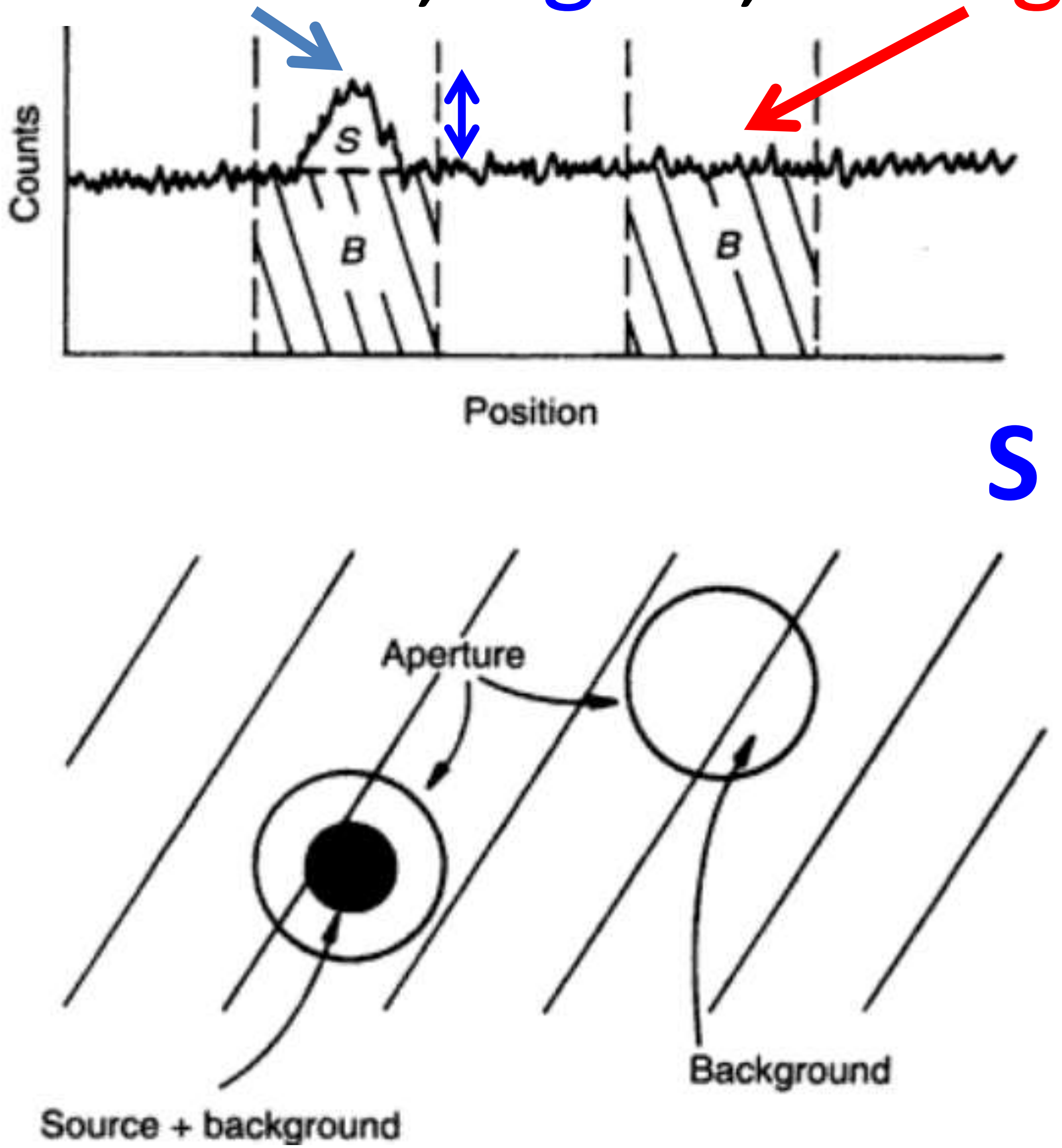


Fig. 3.27. Two extreme examples of noise. In the left-hand diagram, the signal is very weak compared to the background, but is easily detected because the signal-to-noise ratio is large: $S << B$ but $S/N >> 1$. In the right-hand diagram, the signal is comparable in intensity to the background, but its very existence is in doubt because the signal-to-noise ratio is of order one: $S \simeq B$ but $S/N \simeq 1$.

Measurement, signal, background



$$S = M - B$$

Fig. 3.28. The measured signal always includes the background. The vertical dashed lines in the upper diagram, and the circles in the lower diagram, represent the aperture through which the measurements are made (see text).

Measurement, signal, background, noise

- $S = M - B$
- $\sigma_S^2 = \sigma_M^2 + \sigma_B^2$

- Desprezando ruído de leitura e dark current:

$S/N = S/noise = S/sqrt(\sigma_S^2)$

$$S/N = (M - B)/sqrt(\sigma_M^2 + \sigma_B^2)$$

Poisson distribution (of variable x)

Describes distribution in certain counting experiments

Rate (e.g., #contagens/s)

$$P_p(x, \mu) = \frac{\mu^x}{x!} e^{-\mu}$$

Variance = mean

$$\sigma^2 = \mu$$

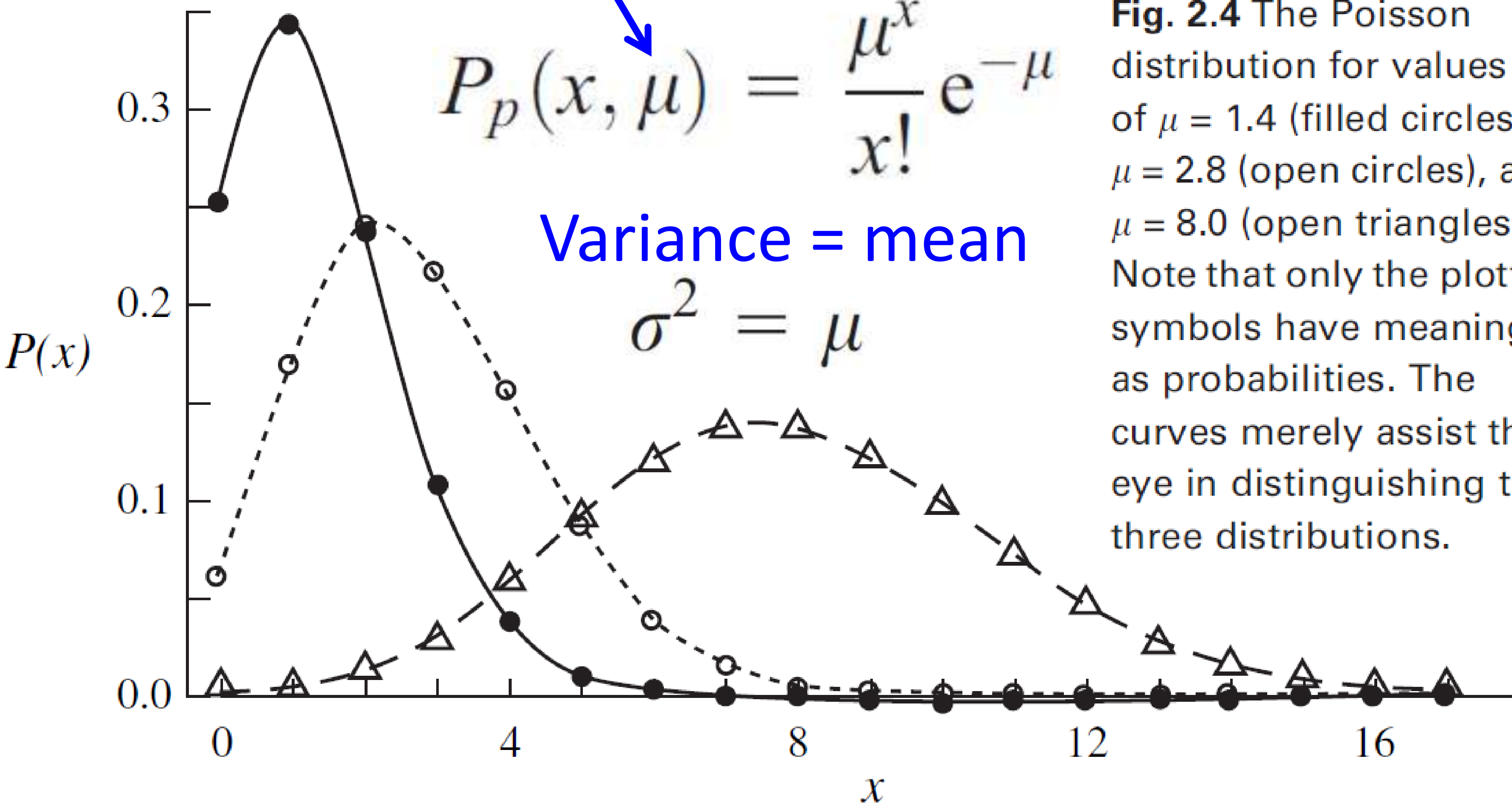


Fig. 2.4 The Poisson distribution for values of $\mu = 1.4$ (filled circles), $\mu = 2.8$ (open circles), and $\mu = 8.0$ (open triangles). Note that only the plotted symbols have meaning as probabilities. The curves merely assist the eye in distinguishing the three distributions.

Measurement, signal, background, noise

- **$S = M - B$**
- **$\sigma_S^2 = \sigma_M^2 + \sigma_B^2$**

- Desprezando ruído de leitura e dark current:

$S/N = S/noise = S/sqrt(\sigma_S^2)$

$S/N = (M - B)/sqrt(\sigma_M^2 + \sigma_B^2)$

$S/N = (M - B)/sqrt(M + B)$

Measurement, signal, background, noise

- **S = M – B**, $\sigma_S^2 = \sigma_M^2 + \sigma_B^2$

S/N = (M - B)/sqrt(M + B)

Se B ~ 0 (p.ex., baixa emissão do céu):

S/N ~ M/sqrt(M)

S/N = sqrt(M)

Exemplo, M=10000 counts, → S/N = 100

Exemplo 1

- 1400 contagens
- ADU = 10
- Bias = 400
- Qual o S/N?

Exemplo 2

- S/N = 30
- Ganho = 3 e-
- Bias = 400
- How many counts are needed per pixel desprezando o céu?

- S/N = sqrt (M), then M = 900 e-
- 900 e- = 300 counts, so 700 counts are needed to achieve S/N = 30 per pixel