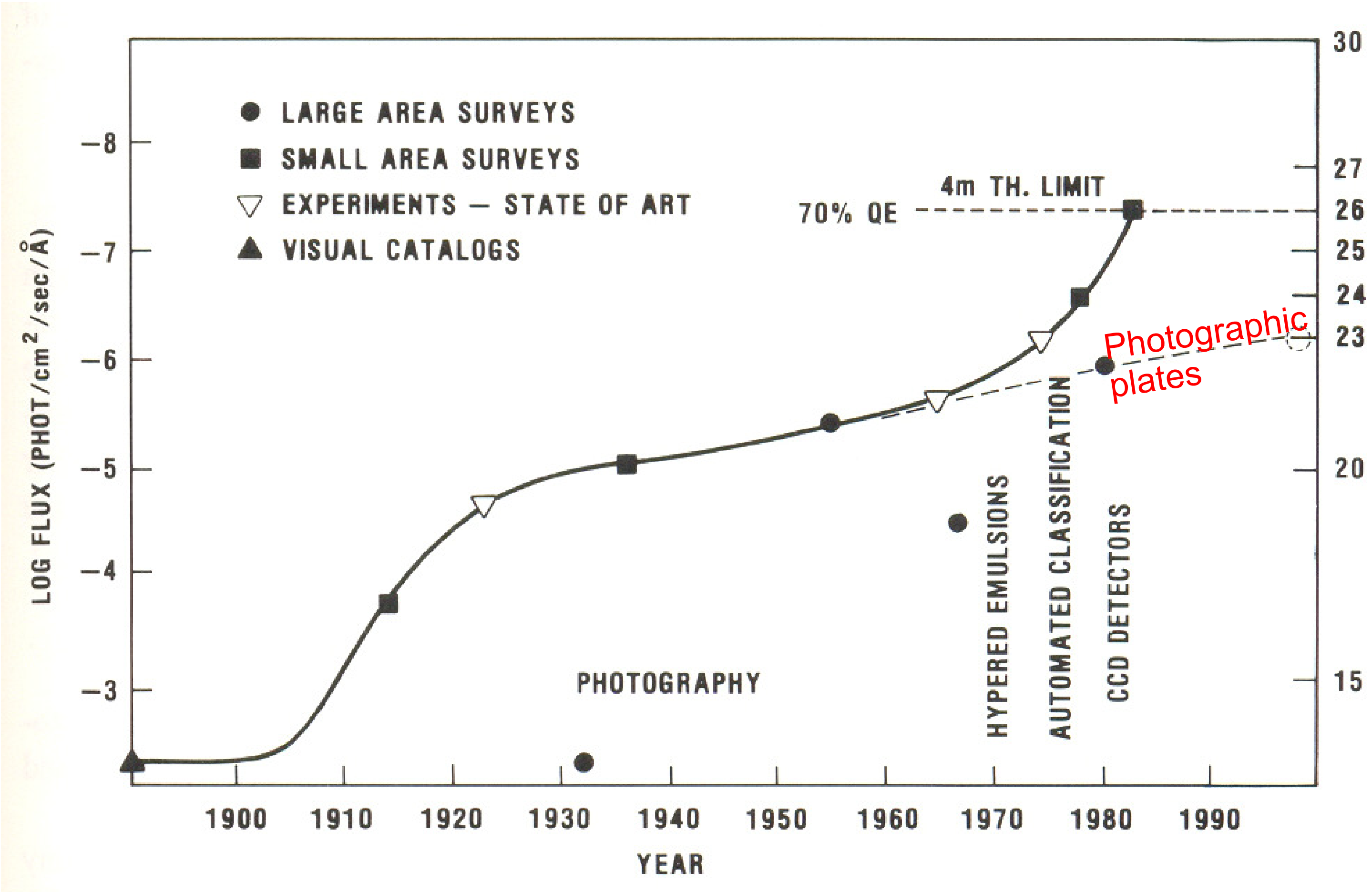
Detection of Light

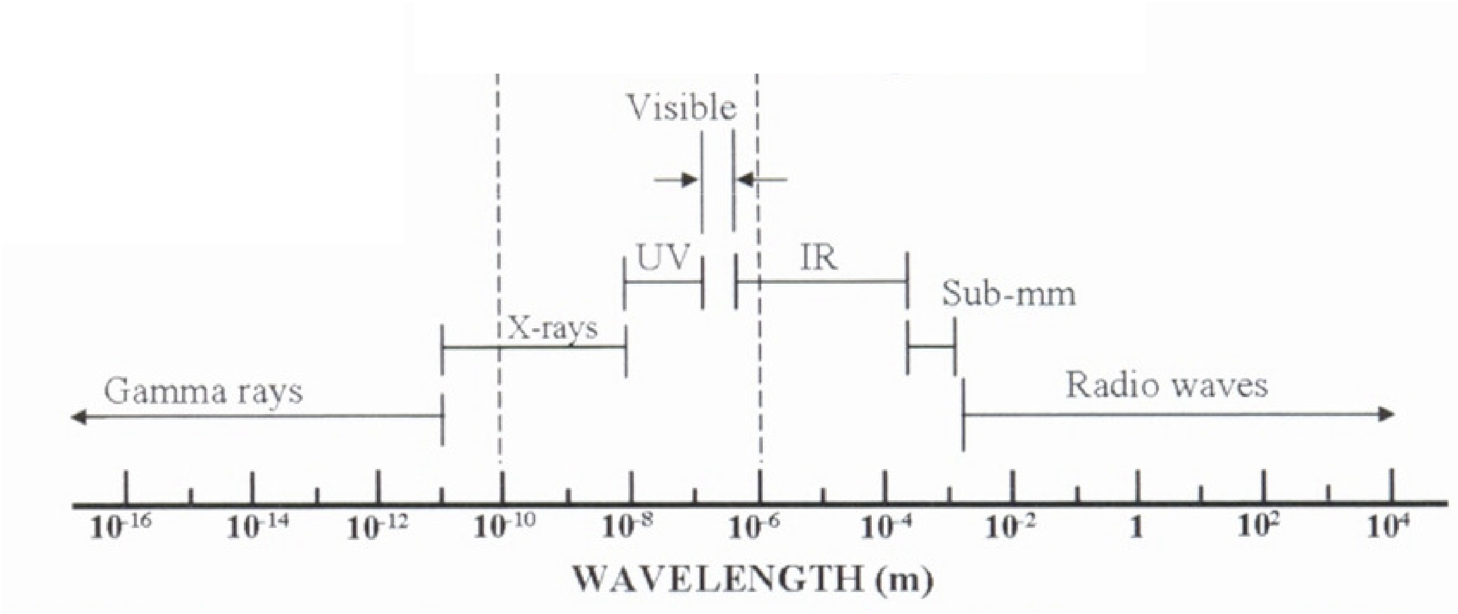
See http://www.strw.leidenuniv.nl/~brandl/DOL/Detection_of_Light.html for more info

Overview of the course topics

The faintest sources detected in optical surveys

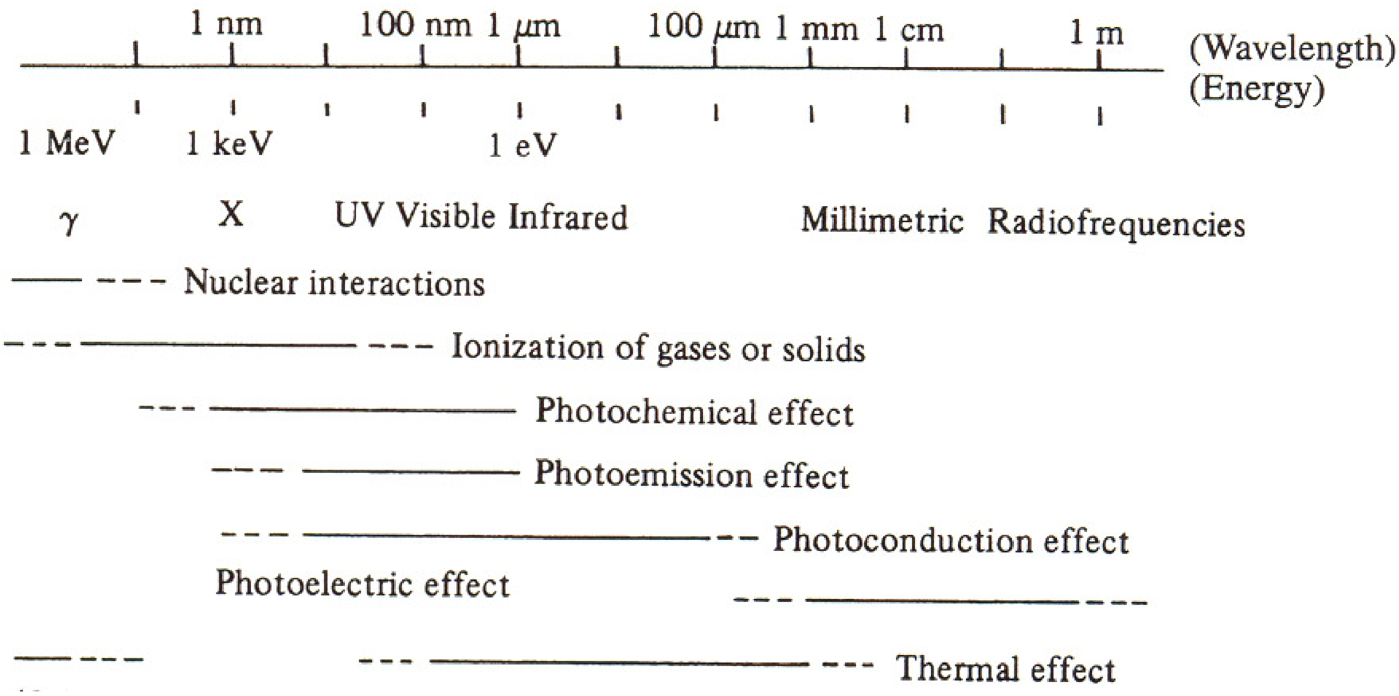


The Electromagnetic Spectrum



covered in this course

Wavelength ⇔ Energy ⇔ Detection Process



Three Basic Types of Detectors

1. Photon detectors

   Respond directly to individual photons → releases bound charge carriers. Used from X-ray to infrared.

   Examples: photoconductors, photodiodes, photoemissive detectors, photographic plates

2. Thermal detectors

   Absorb photons and thermalize their energy → modulates electrical current. Used mainly in IR and sub-mm detectors.

   Examples: bolometers

3. Coherent receivers

   Respond to electrical field strength and preserve phase information (but need a reference phase “local oscillator”). Mainly used in the sub-mm and radio regime.

   Examples: heterodyne receivers

General Principle of Detecting EM Radiation

$$S(t) = S_0(t) + f\left[\int_{\Delta\nu} \phi(\nu)\,d\nu \int_{\Delta\Omega} I(\theta,\nu,t)\,P(\theta)\,d\theta\right]$$

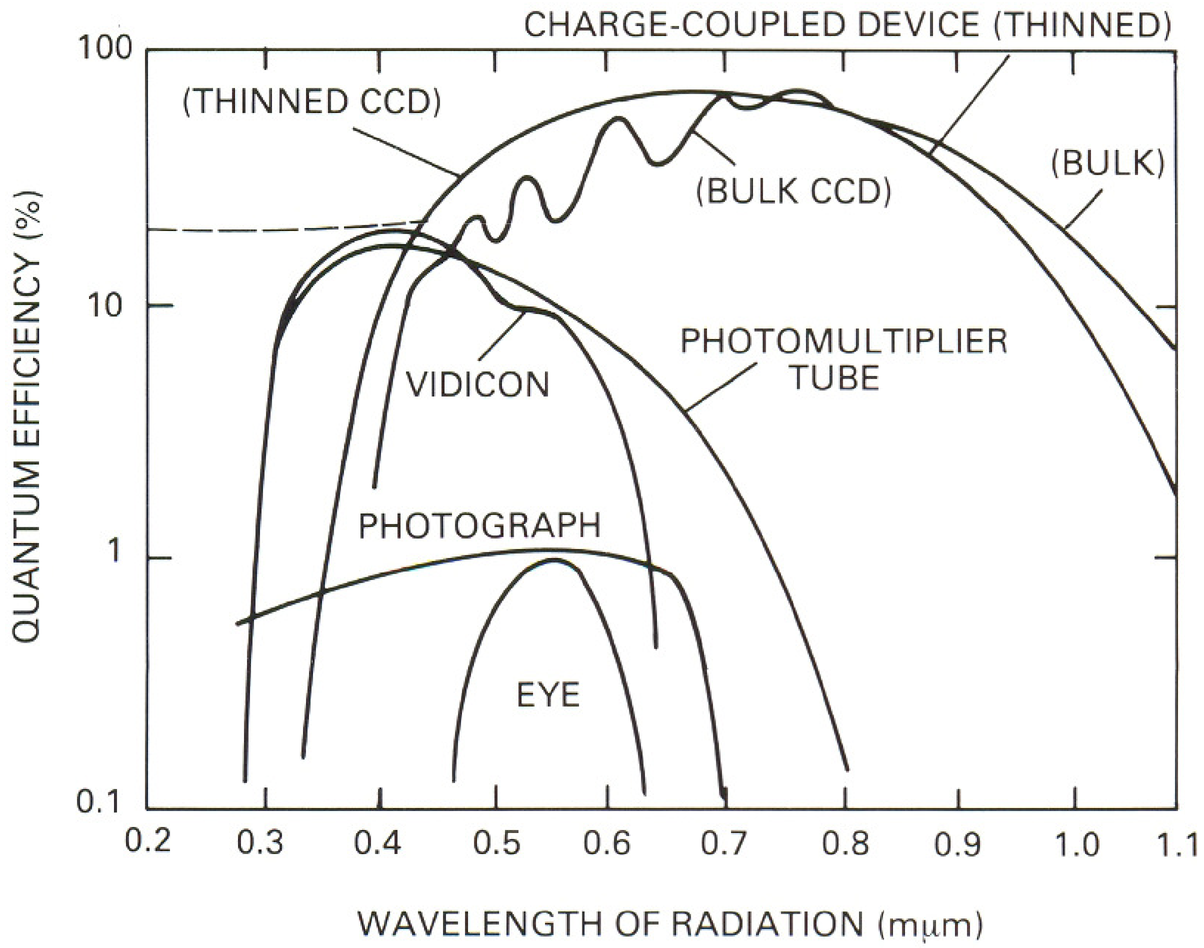
- $S_0(t)$: Dark signal of the detector
- f: Input-output relation of the detector
- $\phi(\nu)$: Spectral response of the detector
- $I(\theta,\nu,t)$: Intensity of the radiation
- $P(\theta)$: Angular response of the detector

Some Detector Performance Aspects

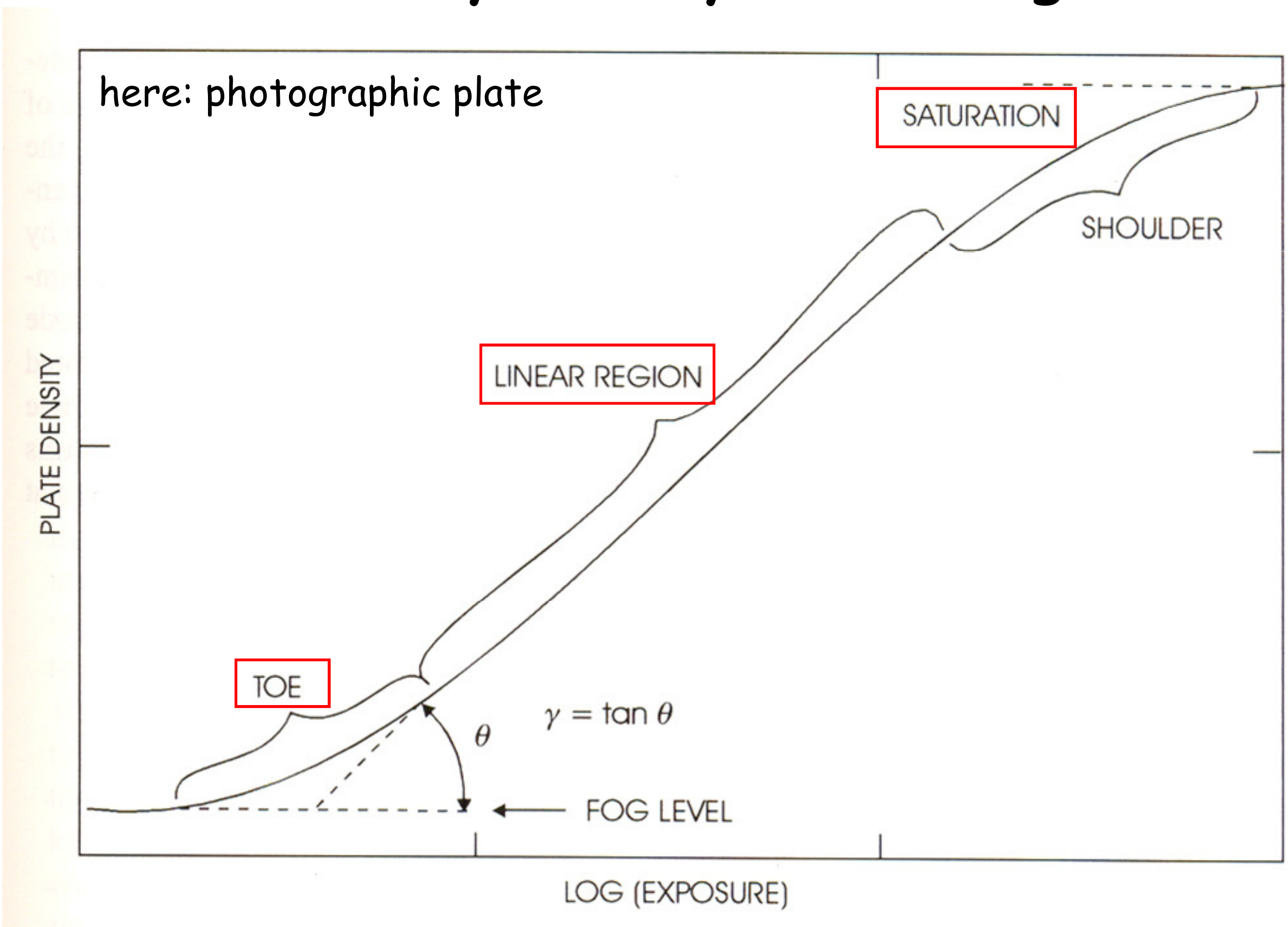
Some Performance Aspects of Detectors

- Spectral response
- Spectral bandwidth
- Linearity / saturation
- Dynamic range
- Quantum efficiency
- Noise
- Geometric properties
- Time response
- Polarization
- Operational aspects

Spectral Response and Bandwidth



Linearity and Dynamic Range



Quantum Efficiency η

$$\eta = \frac{\text{number of detected photons}}{\text{number of incident photons}}$$

Detected photons must:
(i) not be reflected at the detector surface, and
(ii) be absorbed (absorption coefficient a(λ)) within the sensitive detector layer of thickness *l* and refractive index *n*.

Quantum efficiency: $\eta = (1-R)\eta_{abs}$

where: reflectivity at normal incidence: $R \approx \frac{(n-1)^2}{(n+1)^2}$

and photon flux at *l*: $\frac{d\varphi}{dl} = -a(\lambda)\varphi \Rightarrow \varphi = \varphi_0 e^{-a(\lambda)l}$

Fraction of absorbed photons: $\eta_{abs} = \frac{\varphi_0 - \varphi_0 e^{-a(\lambda)l}}{\varphi_0} = 1 - e^{-a(\lambda)l}$

Noise

Most important: $\sigma = \frac{\text{Signal}}{\text{Noise}}$ ← measured as (S+B)-mean{B}

← total noise = $\sqrt{\sum (N_i)^2}$ if statist. independent

<u>Most relevant noise sources:</u>

Photon noise follows Poisson statistics: $P(m) = \frac{e^{-n} n^m}{m!}$

(= probability to detect *m* photons in a given time interval where, on average, *n* photons ➔ $S/N = \sqrt{n}$)

G-R noise: statistics of the generated and recombined holes and electrons, related to the Poisson statistics of the incoming photons.

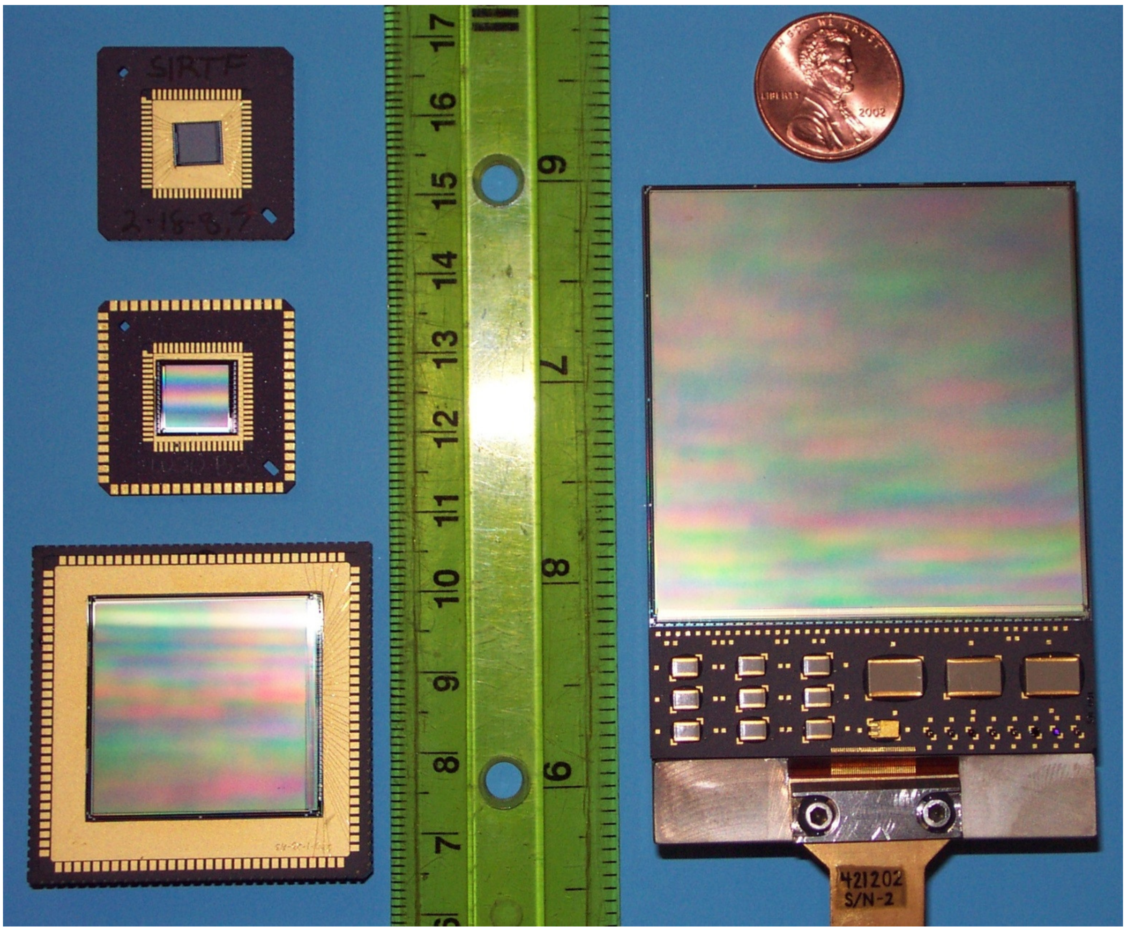
Johnson, kTC or reset noise: thermodynamic noise due to the thermal motion of the charge carriers.

1/f noise (increased noise at low frequencies) due to bad electrical contacts, temperature fluctuations, surface effects (damage), crystal defects, JFETs, …

Geometrical Properties

Geometrical dimension and pixel number x × y

4 Generations of Raytheon Infrared Detectors



Historical distinction: two Detector Types

Single element detectors

+ same pixel = same sensitivity

- scanning = time consuming

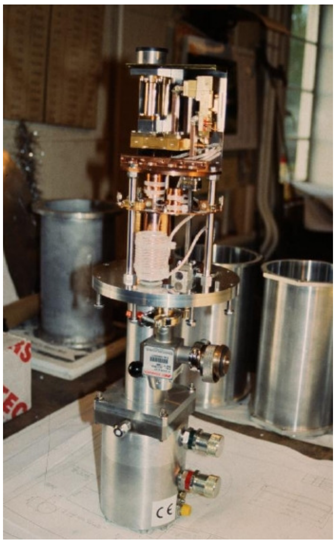
Standard for radio receivers

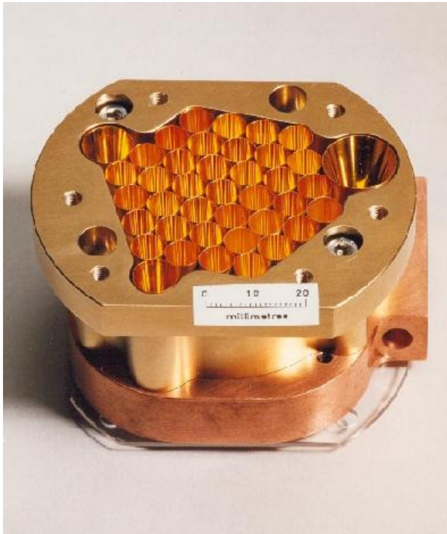
Array size growing at sub-mm

Multi-channel detectors

- flat-field challenge

+ multiplexing speed





Modulation transfer function

…or the "spatial response" of the detector

Assume the detector is exposed to a sinusoidal input signal:

$F(x) = a_0 + a_1 \sin(2\pi f x)$ (a_0 mean height, a_1 amplitude, x distance)

The modulation of the signal is defined as $M_{in} = \frac{F_{max} - F_{min}}{F_{max} + F_{min}} = \frac{a_1}{a_0}$

The detected space frequency is $G(x) = b_0 + b_1(f)\sin(2\pi f x)$

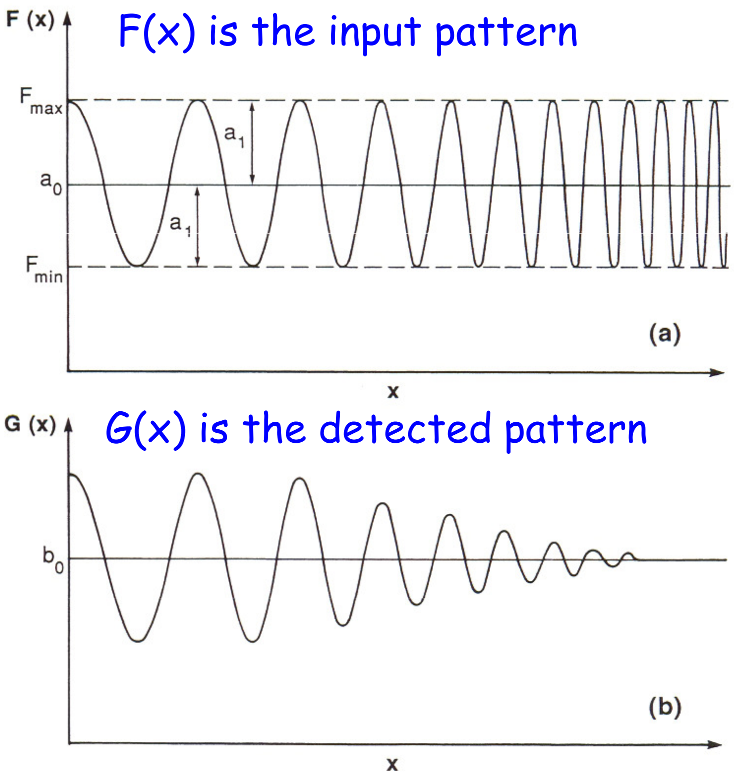
where $b_1(f)$ describes the limited response to higher frequencies. Hence,

$$M_{out} = \frac{b_1(f)}{b_0} \le M_{in}$$

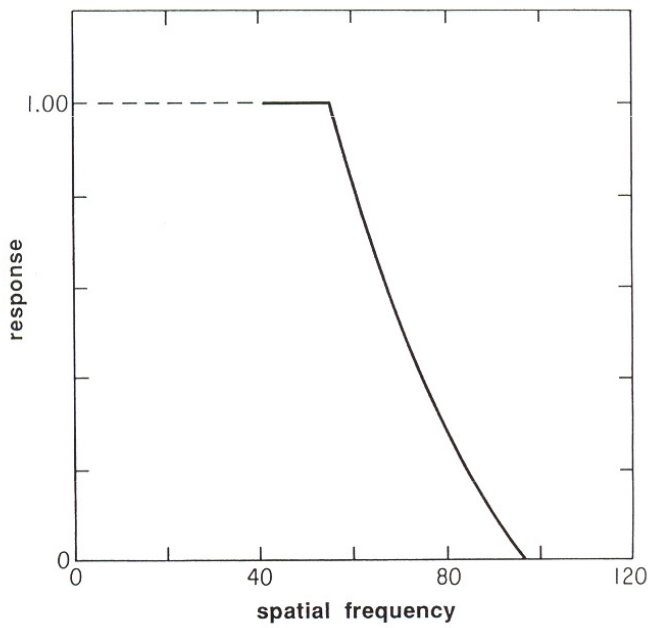
Modulation transfer function (2)

F(x) is the input pattern

G(x) is the detected pattern



The resulting MTF



- The MTF may vary across the array, be color dependent, and suffer from nonlinearities and latent images

Time Response

Astrophysical examples requiring time resolution:

- Stellar black-holes and neutron stars have innermost orbital periods ~ 0.001 seconds
- White dwarfs are eclipsed and pulsate in ~ 0.1 to 200 seconds

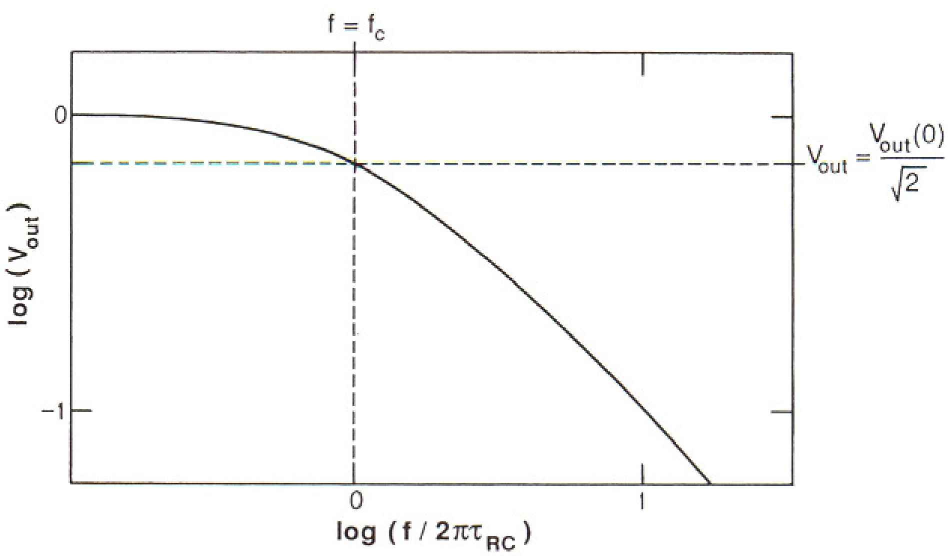
Typical exponential time response of a resistor/capacitor circuit:

$$v_{out} = \frac{v_0}{\tau_{RC}} e^{-t/\tau_{RC}}$$

with τ_{RC}=RC and the cutoff frequency

$$f_c = \frac{1}{2\pi\tau_{RC}}$$

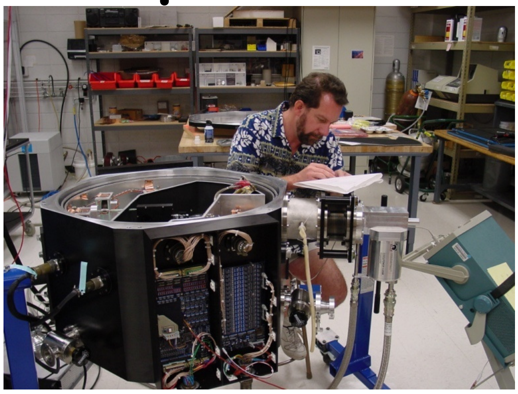
where the signal drops to 1/√2 of its value.



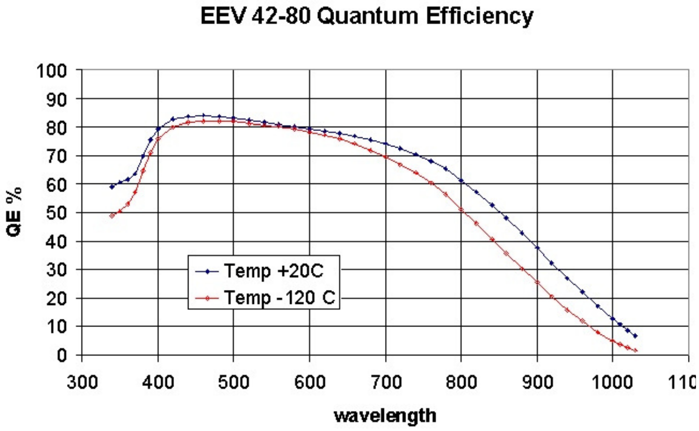
Operational Aspects (1): Temperature

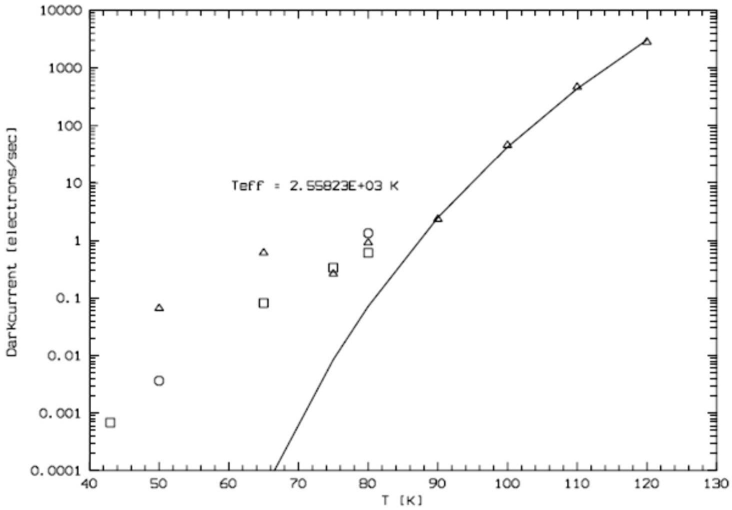
Needs active cooling → 4K … 80K

Maximum temperature ⇔ E_γ



Temperature dependencies of quantum efficiency and dark current





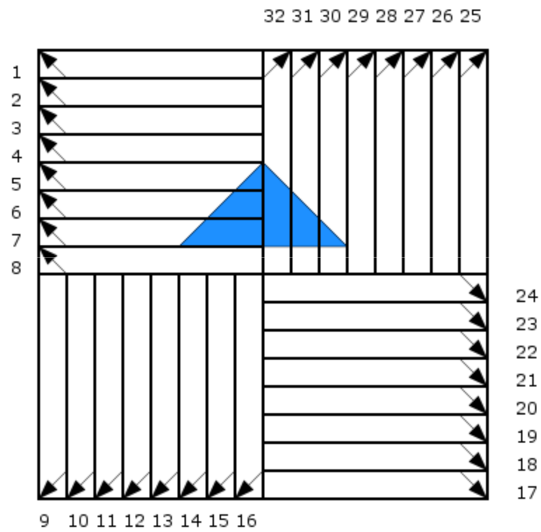
Operational Aspects (2): Readouts

Number of readouts and readout frequencies

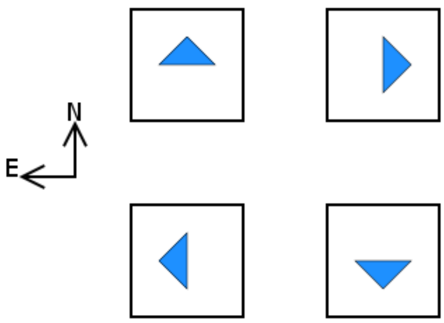
Typical "full frame readout times:

- NIR detector ~few seconds
- MIR space detector ~minute
- MIR ground detector ~10ms

May be problematic if the source moves (e.g., seeing) at the boundaries faster than the readout time.



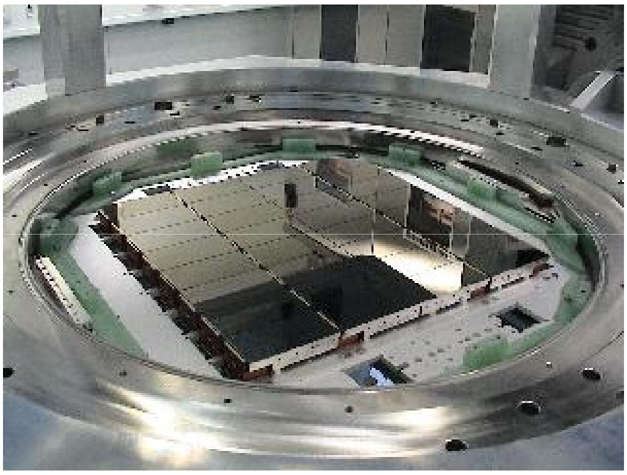
Numbers Round the edge indicate Channel numbers.
Arrows show start-corner of readout



Note that this is only one of many schemes

Orientation of Arrays in Focal Plane

Operational Aspects (3): Data Rates



Example: OmegaCam:

Mosaic of 32 2k×4k CCDs

Read out time: ~45s

Images/night: 10×3600/45 = 800

Number of pixels: 32×2048×4096 = 2.68×10^8

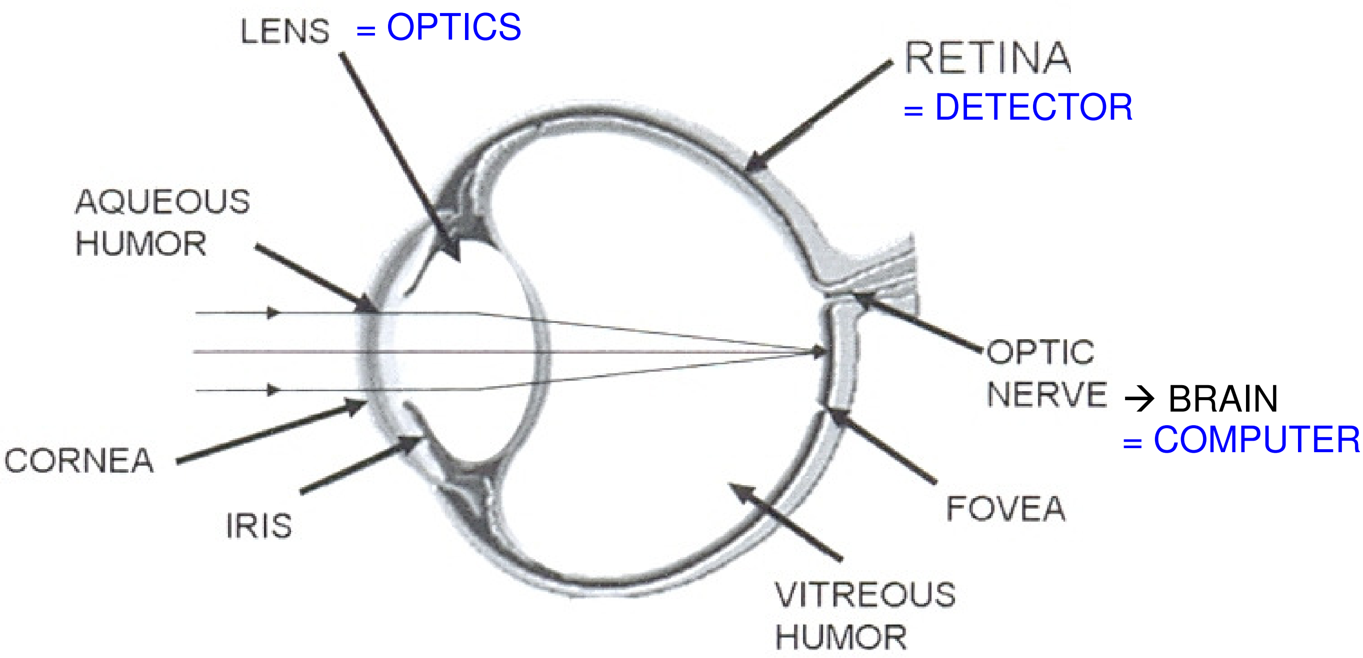
Digitization (16 bits/pixel)*: 16*#ofpixels/(8bits/byte)

→ Total: 429 Gbytes / night (stored data only!)

*(2^{16} = 65536)

The Human Eye

The First Camera: the Human Eye

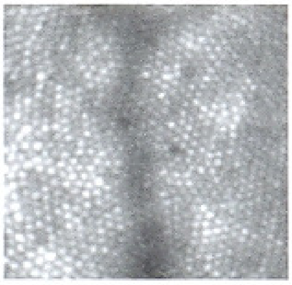


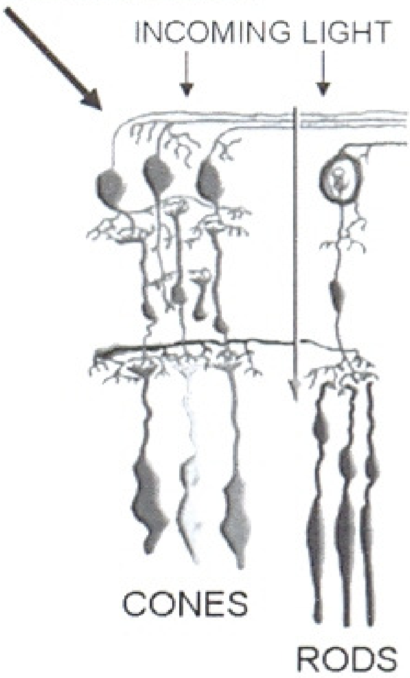
Angular resolution: Theoretical $\Theta \sim \lambda/D \sim 0.5\mu m/7mm \sim 14''$

In practice: $\Theta \sim 1'$

Focal ratio $f/D \sim 3.2$

The Detector: the Retina





Four kind of detectors (~125 millions):

Rod cells (~2μm): panchromatic, low light levels, make up 95%

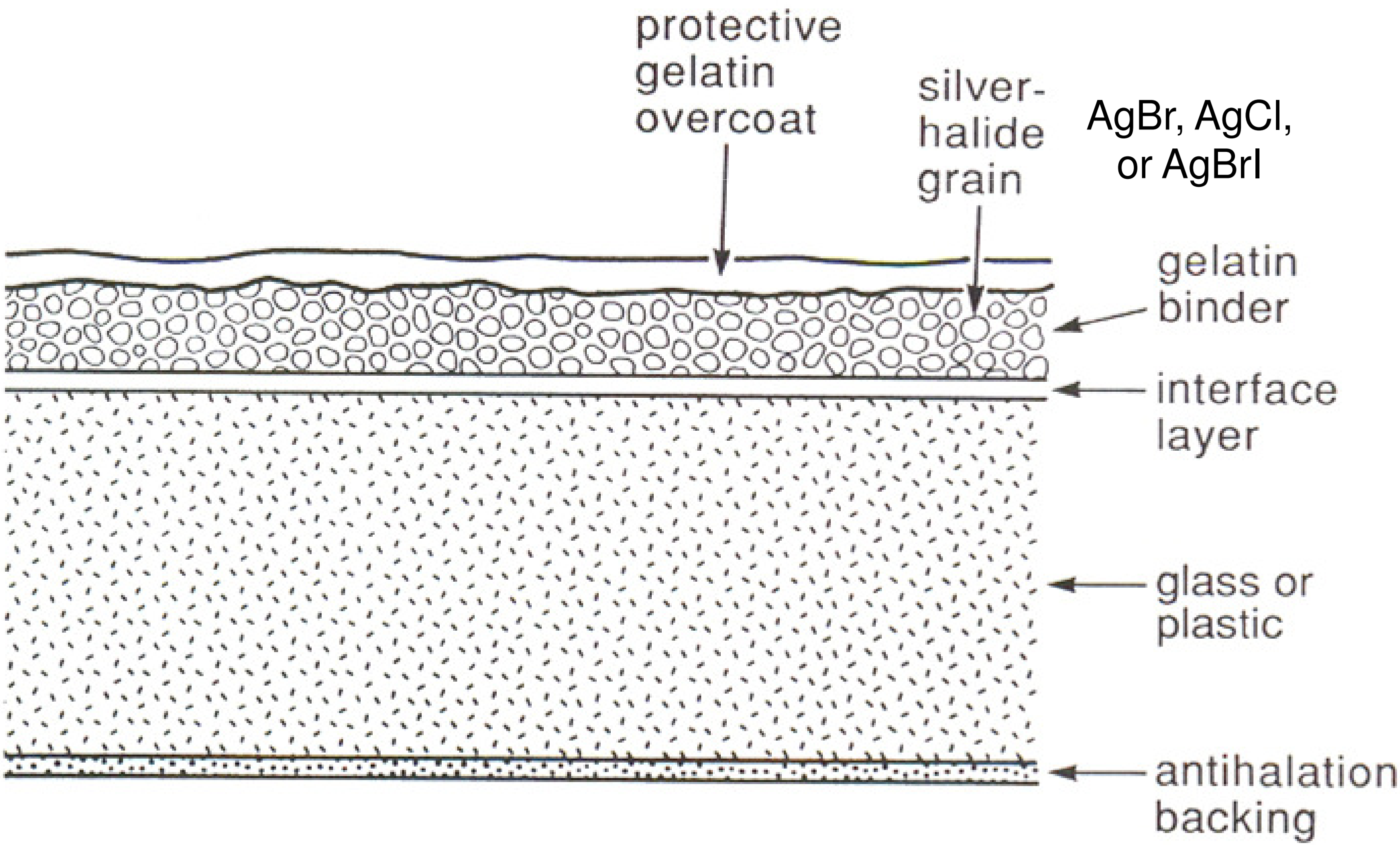
3 types of cone cells (~6μm): blue, green, red sensitive [1:4:8], concentrated to the center

Detector properties (data sheet):

- Wavelength range: $390nm \leq \lambda \leq 780nm$
- Readout frequency ~ 30 Hz
- High dynamic range: $10^9 : 1$
- Sensitivity: "dark adaptation" (t_{int}, η)
- Irregularities (artefacts):
  - averted vision (off-center)
  - latent images (eye⇔brain)
  - others: Purkinje effect, Haidinger's brush

Photographic Plates

Cross section of a typical photographic plate



Basic Principle

1. Expose grains of slightly soluble silver halide salts, e.g.

$$Ag^{+}Br^{-} + \gamma \rightarrow Ag^{+} + Br + e^{-}$$

2. e^{-} recombines:

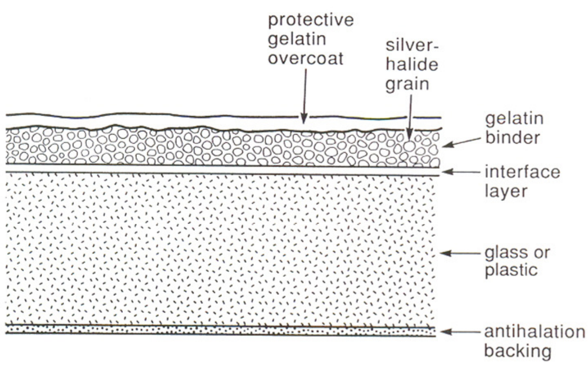
$$e^{-} + Ag^{+} \rightarrow Ag$$
$$e^{-} + Ag \rightarrow Ag^{-}$$
$$Ag^{-} + Ag^{+} \rightarrow Ag_2$$

(critical size: 3–4 Ag atoms)

3. chemical development: (i) provides e^{-} for the "undeveloped" Ag^{+} to reduce them to "inactive" metallic silver, and (ii) amplify the Ag grains by $10^8 - 10^9$

4. Unexposed silver is eliminated by the "fixing" process

Wavelength Coverage



UV is limited due to absorption of the gelatine at $\lambda \leq 300$nm

Bandgap E_g of AgBr is ~2.8 eV (λ < 440nm for direct absorption)

Addition of iodine (→ silver iodobromide) reduces E_g → wider $\Delta\lambda$

Adding a dye to the emulsion → green, red

Out to 1.2μm (Kodak 1-Z emulsions)

Advantages of Photographic Plates

- A 8″ – 10″ plate can have 10^{11} – 10^{12} grains, corresponding to 10^9 "pixels"
- Plates are inexpensive
- Plates are their own data storage system
- Plates can be stable over very long periods of time

Disadvantages of Photographic Plates

- Low DQE (~2-5%) [e^- may recombine, ionize Ag atom, react with gelatine]
- Non-linearity
- Non-uniformity
- Time resolution
- Wavelength coverage
- Digitization

Observing with Photoplates

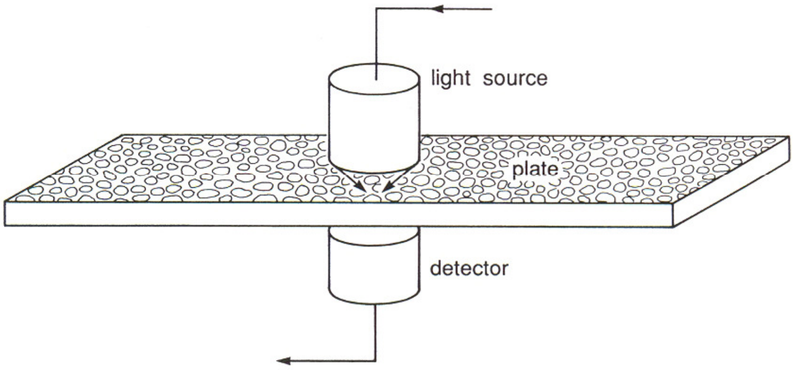
Photographic Plates

TABLE V-12: PHOTOGRAPHIC PLATE STOCK AT CTIO

	(cm.)	20.3x25.4x0.15	19.7x19.7x0.10
	(in.)	8x10x0.06	7.75x7.75x0.04
Telescope		4.0- and 1.5-meter Telescopes	Curtis-Schmidt
	103aD	x	x
	IIaO	x	x
	IIIaJ	x	x
	IIaD	x	x
	IIIaF	x	x
	098-04	x	x
	I N	x	x
	IV N	x	x

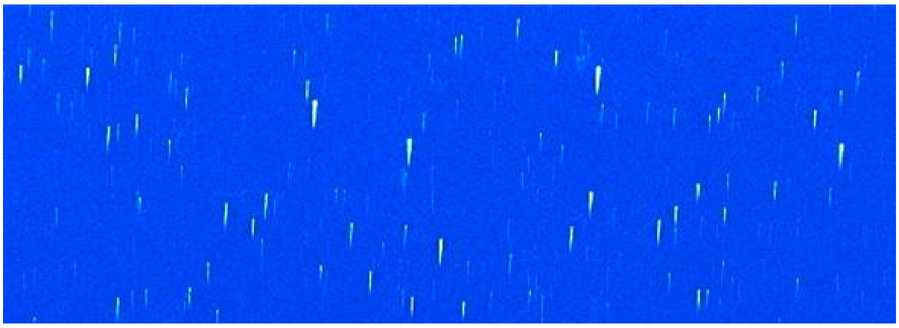
Analysis of Photographic Plates

Densitometer!



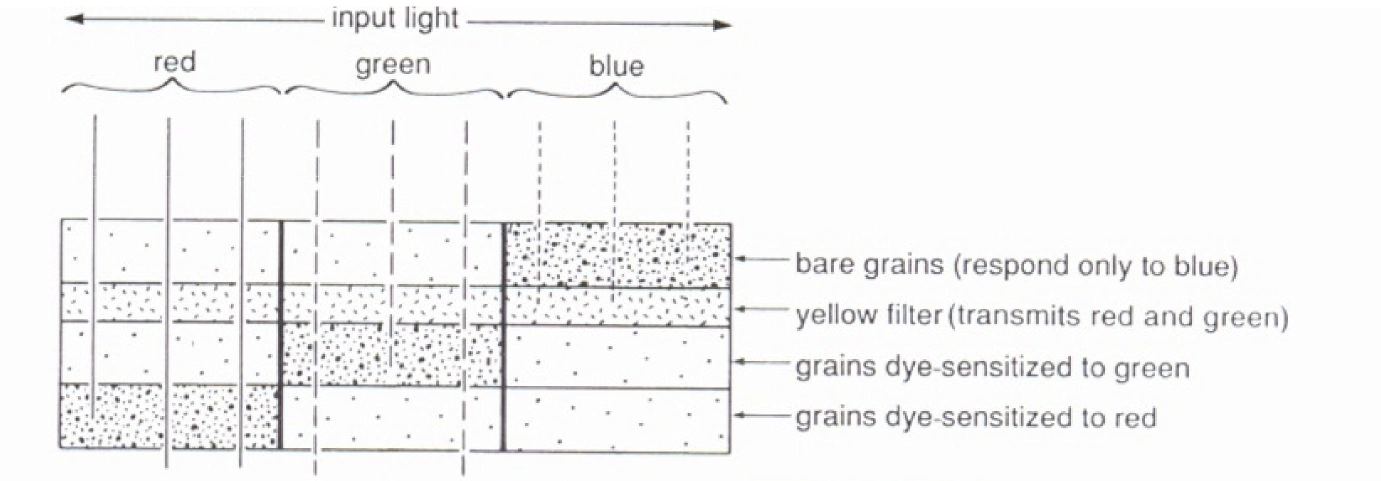
Density d = $-\log_{10} I / I_0$

Nowadays using scanners, e.g. for the Digitized First Byurakan Survey (DFBS) →



Color Photography (1)

Exposure of the emulsion layers to the three primary colors

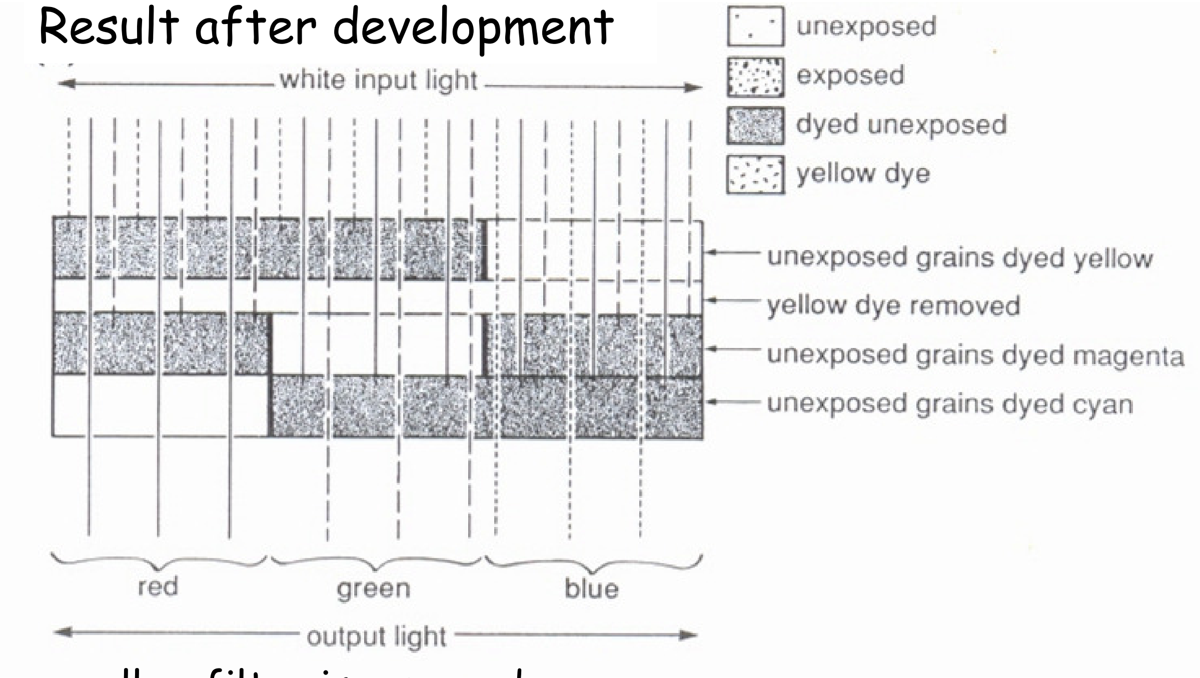


Depthwise superposition of emulsions

- top layer responds only to blue light
- yellow filter removes blue light (transmits green and red
- the dye-sensitized layers underneath respond to green and to red (either one)

Color Photography (2)

Result after development



- yellow filter is removed
- layer-by-layer dyes are produced in emulsion layers
- at the end, all silver has been removed and the image dyes remain

For details see Rieke book, section 8.2.4