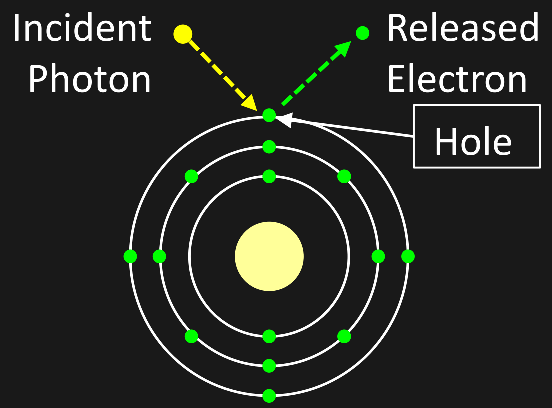
Photons to images

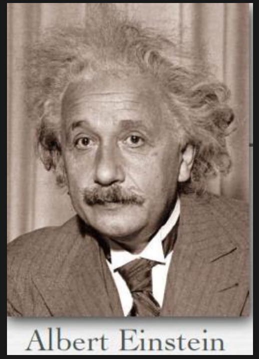
January 3, 2018

Digital imaging pipeline

Photons to electrons

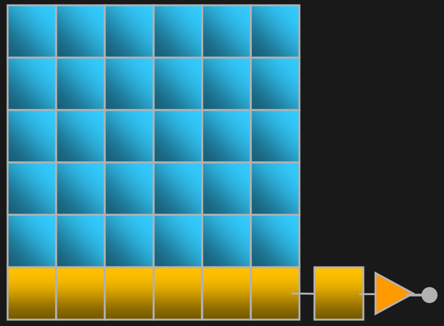


Silicon Atom

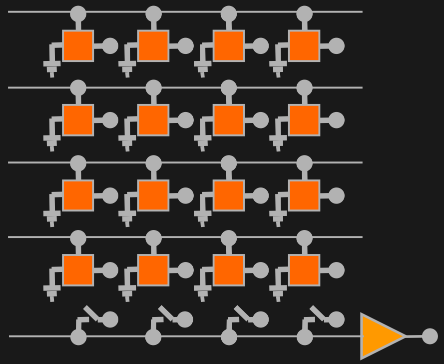


Electrons to voltage conversion

CCD

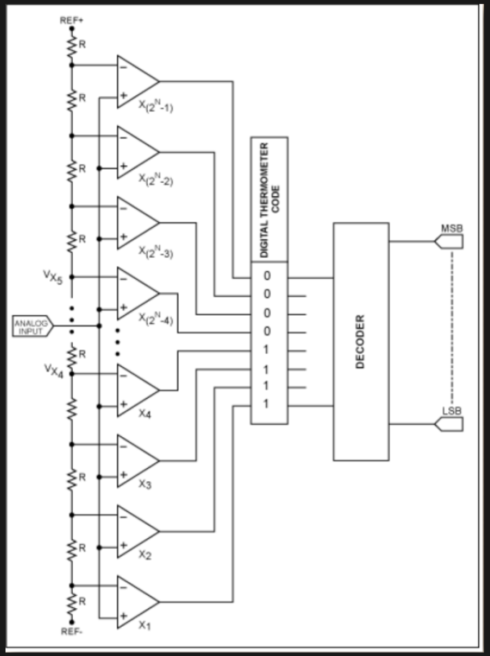


CMOS

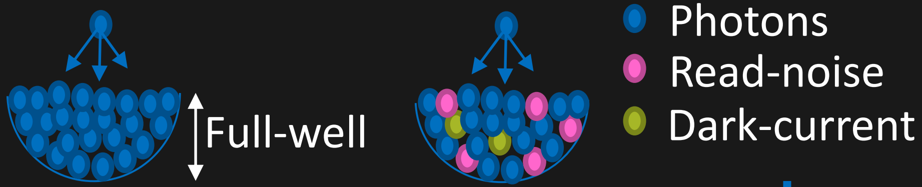


Voltages to gray levels

ADC



Sources of noise

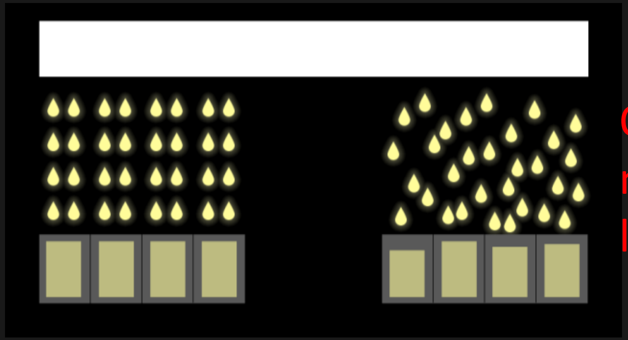


Photons to electrons

1. Photon shot noise

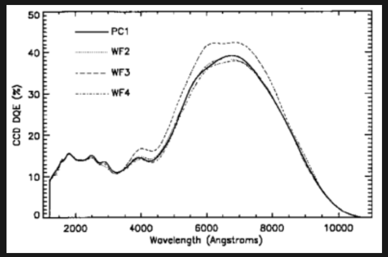
Expectation

Reality



Quantum nature of light

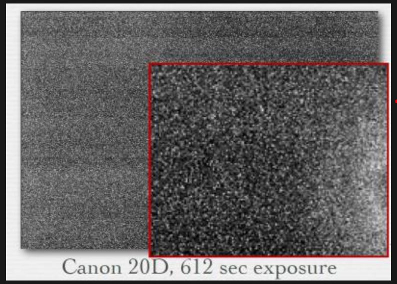
2. Quantum Efficiency



$$QE = \frac{\#electrons}{\#photons}$$

Electrons to voltage conversion

1. Dark current noise



Thermally generated electrons

2. Full-well capacity

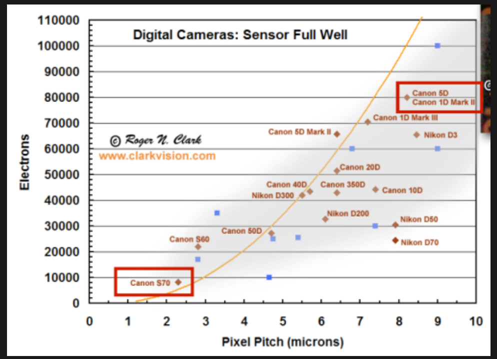
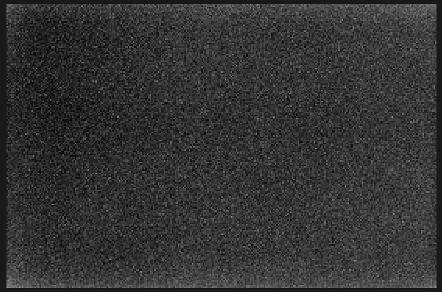


Image saturation

Voltages to gray levels

1. Read noise



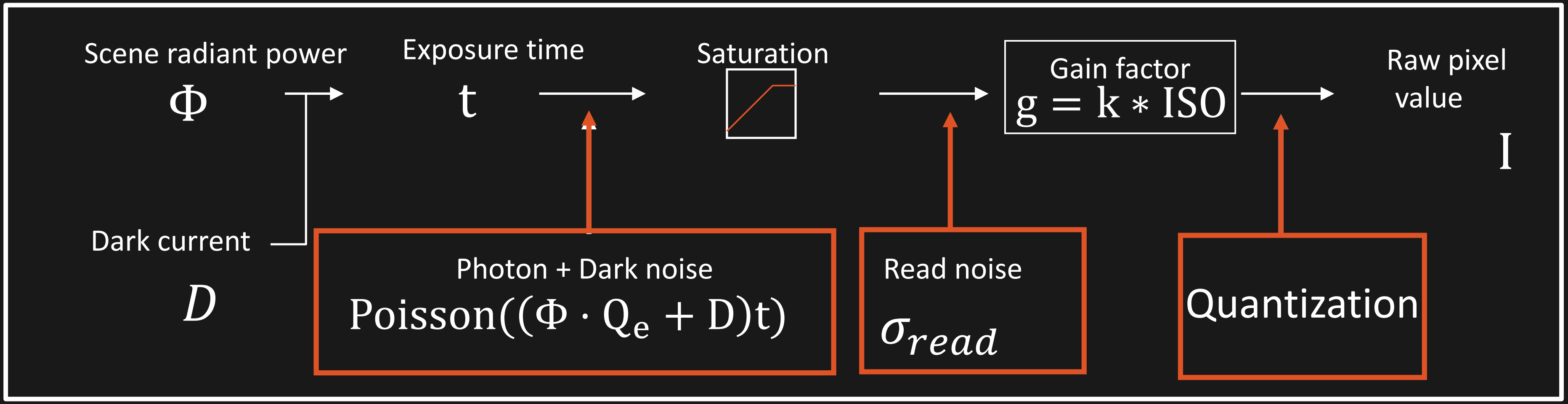
Thermal noise in read-out circuitry

2. Systematic noise

- Fixed-pattern noise
- Pixel readout non-uniformity
- Hot-pixels

Ignore for now

Per-pixel noise model



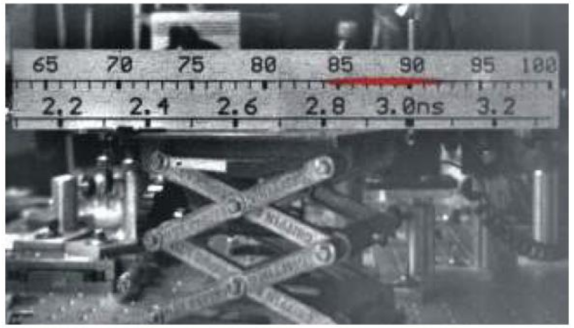
linear image formation:

Saturation level/Full-well

$$\boxed{I = \underbrace{g}_{\text{Gain}} * \left(\min\left(\mathrm{Poisson}\left((\Phi \cdot Q_e + D)t\right), I_{max}\right) + \underbrace{n}_{\text{Noise (Read)}}\right)}$$

Intensified CCD camera (ICCD): 4 Picos

Single-photon sensitivity   Stanford Computer Optics   Temporal Resolution: 200 ps

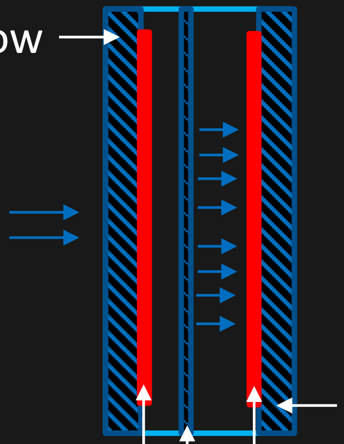


The image shows the distance a femtosecond laser pulse moved along a ruler while the shutter of the 4 Picos camera was open. This distance is a direct measure of the flat top, single shot gating time.

Example image: Shows that the laser moved approximately ~ 200 ps.

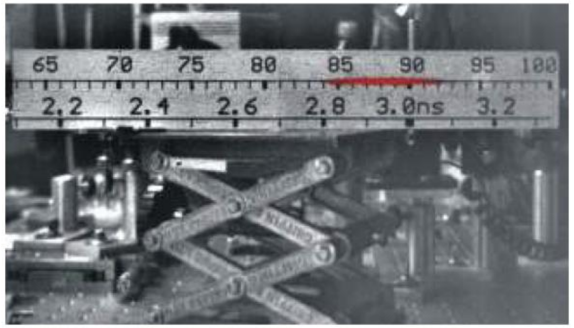
Intensified CCD camera (ICCD): 4 Picos

Intensifier



- **Photocathode:** 50% (peak)
- **MCP** : 1000 × electron multiplication
- **Phosphor** : 180 photons per electron

Stanford Computer Optics



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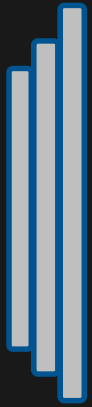
CCD



- High-dynamic range : 12 bits
- High TE cooling ($-40°C$): Low-dark current

Intensifier specification

- Quantum-efficiency : $50\ \%$
- MCP (amplification) : $1000\ \times$
- Phosphor-efficiency : 180 photons per electron

- Dark-current : $0.2\ \frac{\text{electrons}}{\text{pix}}/\text{sec}$

CCD specification

- Resolution : 1360×1024
- Dynamic-range : 12 bit
- Pixel-Size (μm) : 4.7×4.7

- Quantum-efficiency : $40\ \%$
- Dark-current : $0.2\ \frac{\text{electrons}}{\text{pix}}/\text{sec}$
- Read-noise : 7 electrons
- Full-well : $500{,}000\ e^{-}$
- Quantization-bits : 12 bits

Pseudocode: Forward-model

[outputImage] = ScatteringMedium (PSF, reflectivity)

PSF : 2D-Point-spread function in $\frac{\text{photons}}{\text{unit-time}}$

reflectivity : Scene-reflectivity in $[0,1]$

outputImage: Output-image in $\frac{\text{photons}}{\text{unit-time}}$

$\text{outputImage} = \text{imfilter}(\text{PSF}, \text{Reflectivity}, '\text{same}');$

[intensifiedOutput] = ICCDIntensifier (outputImage)

outputImage : Image incident on intensifier in $\frac{\text{photons}}{\text{unit-time}}$

intensifiedOutput: Intensified output-image in $\frac{\text{photons}}{\text{unit-time}}$

q_e : 0.5 (Quantum-efficiency of intensifier in $\frac{\text{electrons}}{\text{photons}}$)

dc : 0.2 (Dark-current in $\frac{\frac{\text{electrons}}{\text{pixel}}}{\text{second}}$)

mcp : 1000 (Amplification of electrons)

pe : 180 (Phosphor-screen efficiency in $\frac{\text{photons}}{\text{electrons}}$)

$\text{intensifiedOutput} = \text{poisson}(\text{outputImage} \times q_e + \text{dc} \times \Delta t) \times \text{mcp} \times \text{pe}$

[imagePixels] = CCDSensor (intensifiedOutput, x)

intensifiedOutput : Intensified output-image in $\frac{\text{photons}}{\text{unit-time}}$

outputImage : Output-image in $\frac{\text{photons}}{\text{unit-time}}$

q_e : 0.4 (Quantum-efficiency of sensor in $\frac{\text{electrons}}{\text{photons}}$)

dc : 0.2 (Dark-current in $\frac{\frac{\text{electrons}}{\text{pixel}}}{\text{second}}$)

rn : 7 (Read-noise in $\frac{\text{electrons}}{\text{pixel}}$)

fw : 500,000 (Full-well capacity in $\frac{\text{electrons}}{\text{pixel}}$)

g : x (Gain-factor decided by which image saturates)

nb : 12 (Number of bits in bits)

$\text{imageInElectrons} = \text{poisson}(\text{intensifiedOutput} \times q_e + \text{dc} \times \Delta t)$

$\text{imageInElectrons} = \min(\text{imageInElectrons}, \text{fw})$

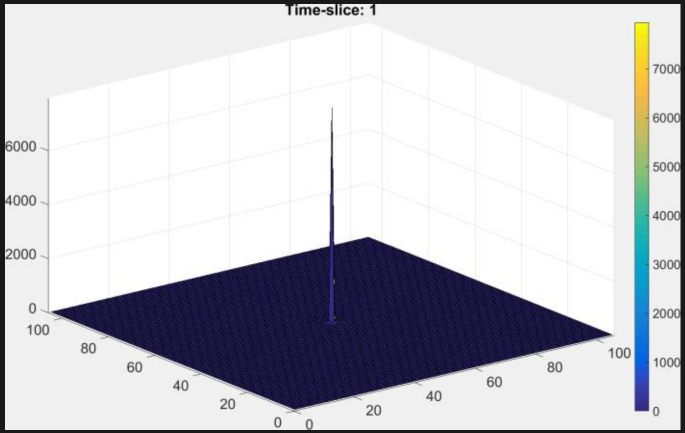
$\text{imageInElectrons} = \text{AWGN}(\text{imageInElectrons}, \text{rn}^2)$

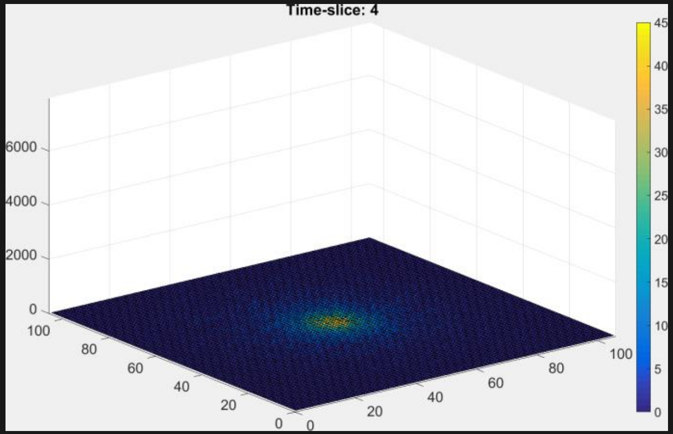
$\text{imageInVolts} = \text{imageInElectrons} \times \text{g}$

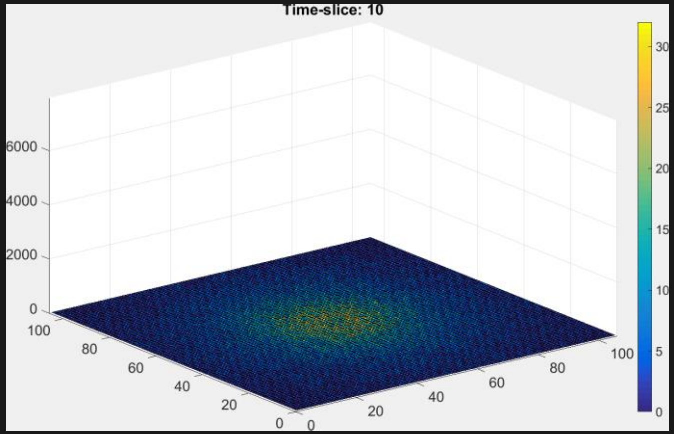
$\text{imageInPixels} = \text{binarize}(\text{imageInVolts}, \text{nb})$

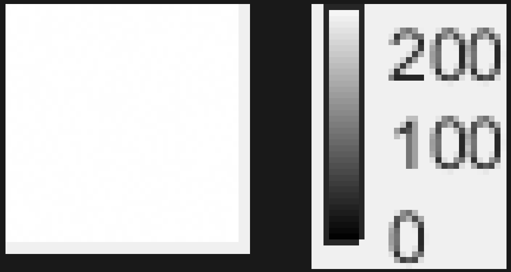
Example forward-model

$$\text{TotalNumberPhotons} = 1e9$$





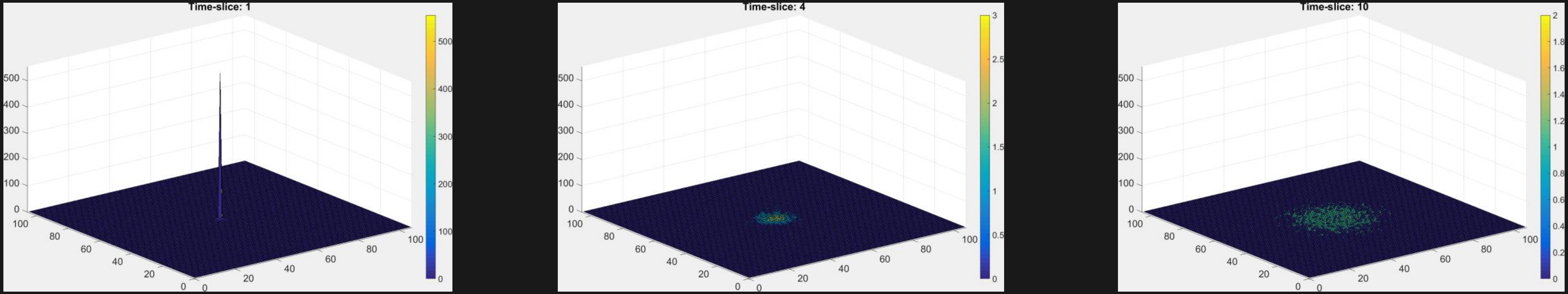




Intensifier-gain	1
Saturated-image	5

Example forward-model

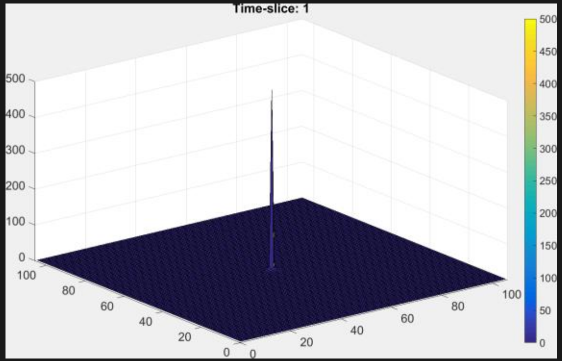
$$\text{TotalNumberPhotons} = 1e7$$

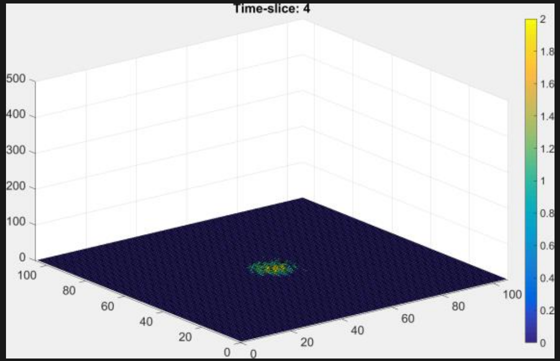


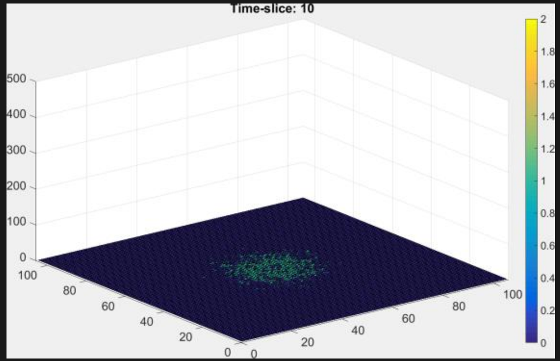
Intensifier-gain	21
Saturated-image	11

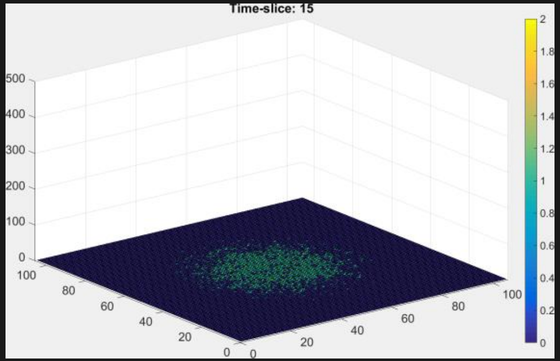
Example forward-model

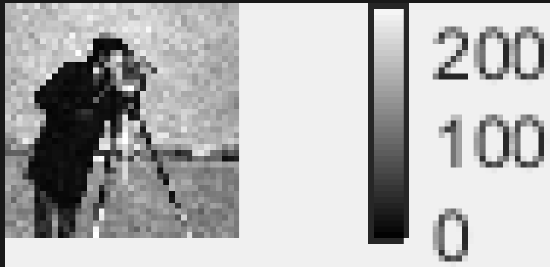
$$\text{TotalNumberPhotons} = 0.9e7$$

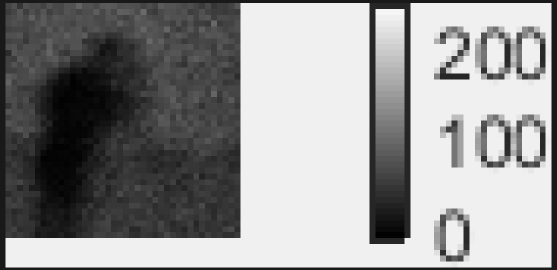


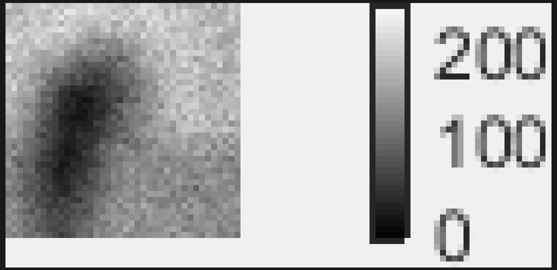


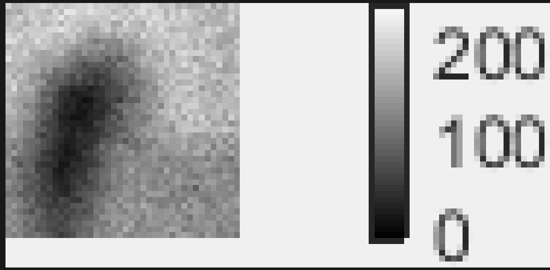








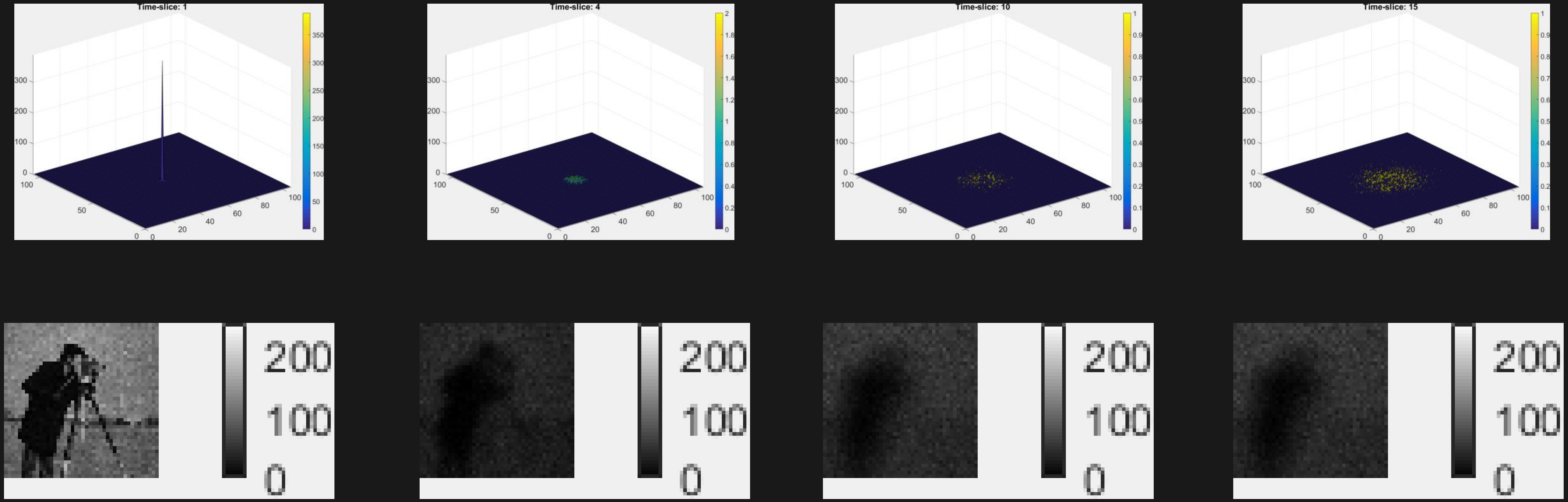




Intensifier-gain	24
Saturated-image	11

Example forward-model

$$\text{TotalNumberPhotons} = 0.7e7$$



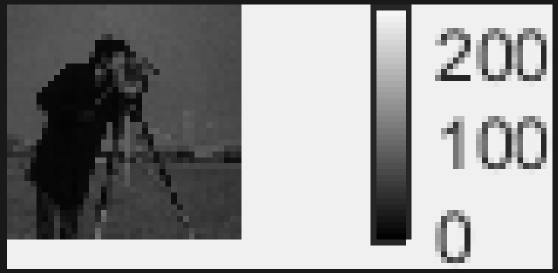
Intensifier-gain	24
Saturated-image	17

Intensifier gain

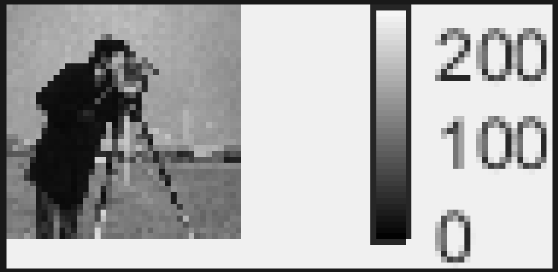
$\text{TotalNumberPhotons} = 1e8$

Increasing the intensifier-gain saturates the image more quickly (in time) but the quality of the slice-1 seems to improve.

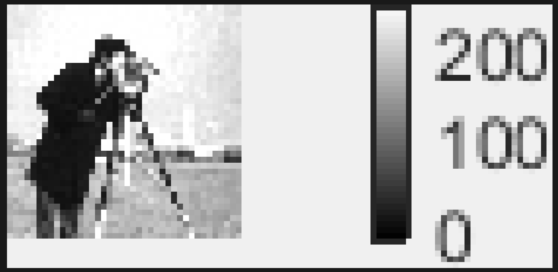
Intensifier gain = 1
Saturated image= 8



Intensifier gain = 2
Saturated image= 5



Intensifier gain = 3
Saturated image= 1

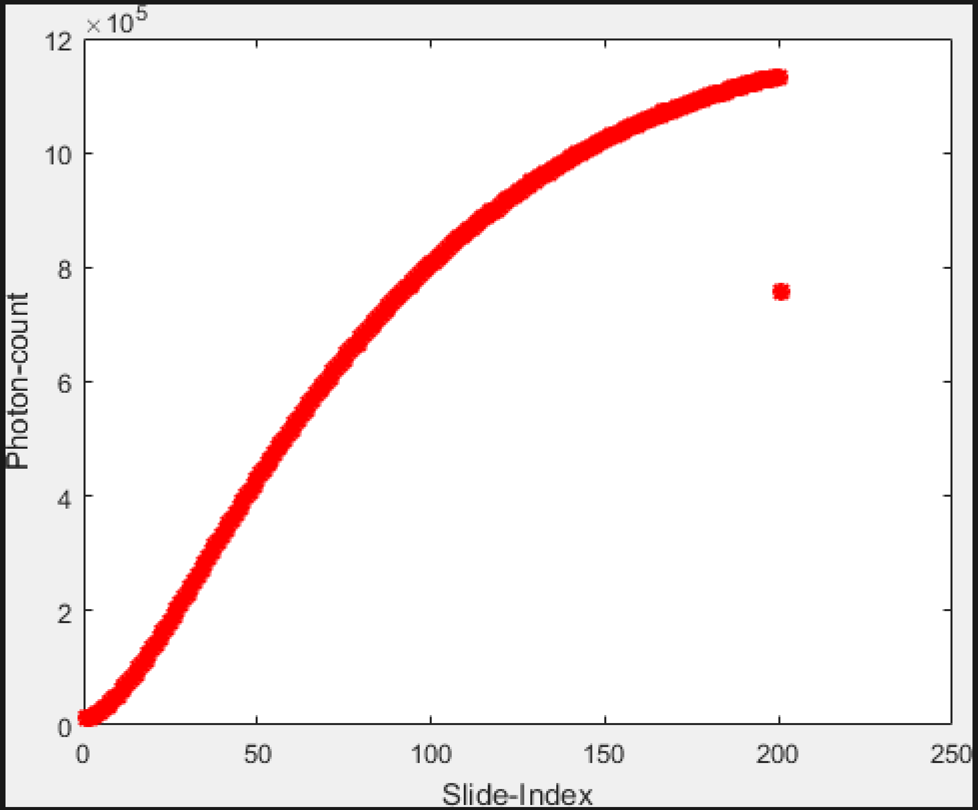


Intensifier gain = 4
Saturated image= 1

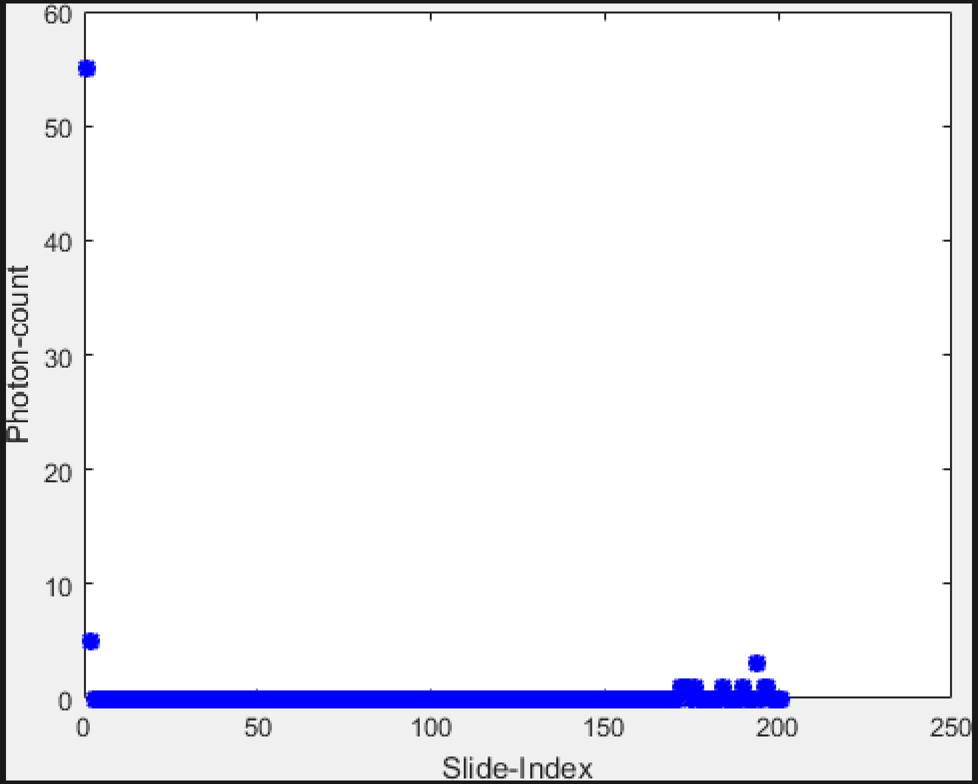
Low-photon count issue

Photon-count adjustment formula:

$$\mathbf{NewPSF} = \mathbf{floor}\left(\frac{\mathbf{NewPhotonCount}}{\mathbf{OldPhotonCount}} * \mathbf{OldPSF}\right)$$



Old-photon count



New-photon count