# Overcoming the Full Well Capacity Limit: High Dynamic Range Imaging Using Multi-Bit Temporal Oversampling and Conditional Reset

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# Binary Image Sensors

- Images are reconstructed from binary oversampling
- Each pixel has $S$ jots (units of spatial oversampling) which are binary oversampled $N$ times per exposure
- The expected pixel response can be calculated as the sum of samplings above threshold

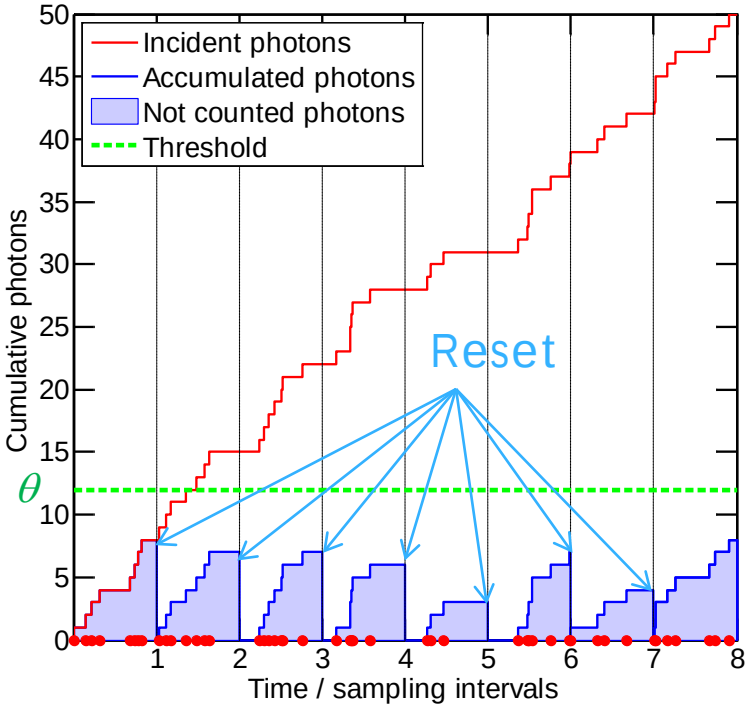
$$\mathbb{E}(Y) = \sum_{i=1}^{S} \sum_{m=1}^{N} p_{i,m}$$

$p_{i,m}$: Probability of jot $i$ to be at or above threshold at end of interval $m$

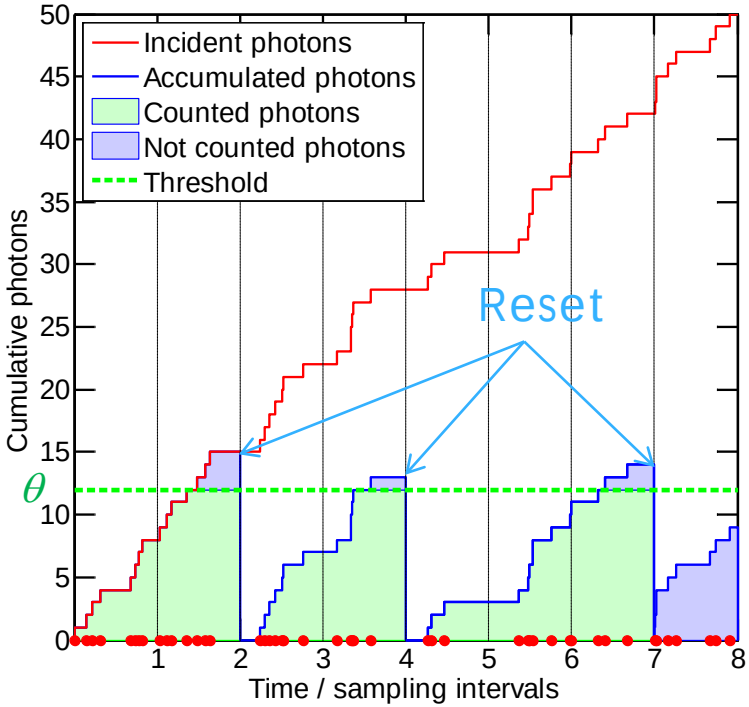
- The probability $p_{i,m}$ is calculated by repeated sampling from Poisson distributions (either with analytical model or Monte Carlo simulation)

# Pixel Reset

## Unconditional reset




## Conditional reset




- Conditional reset enables binary sampling with thresholds larger than single photon

# Multi-Bit Oversampling

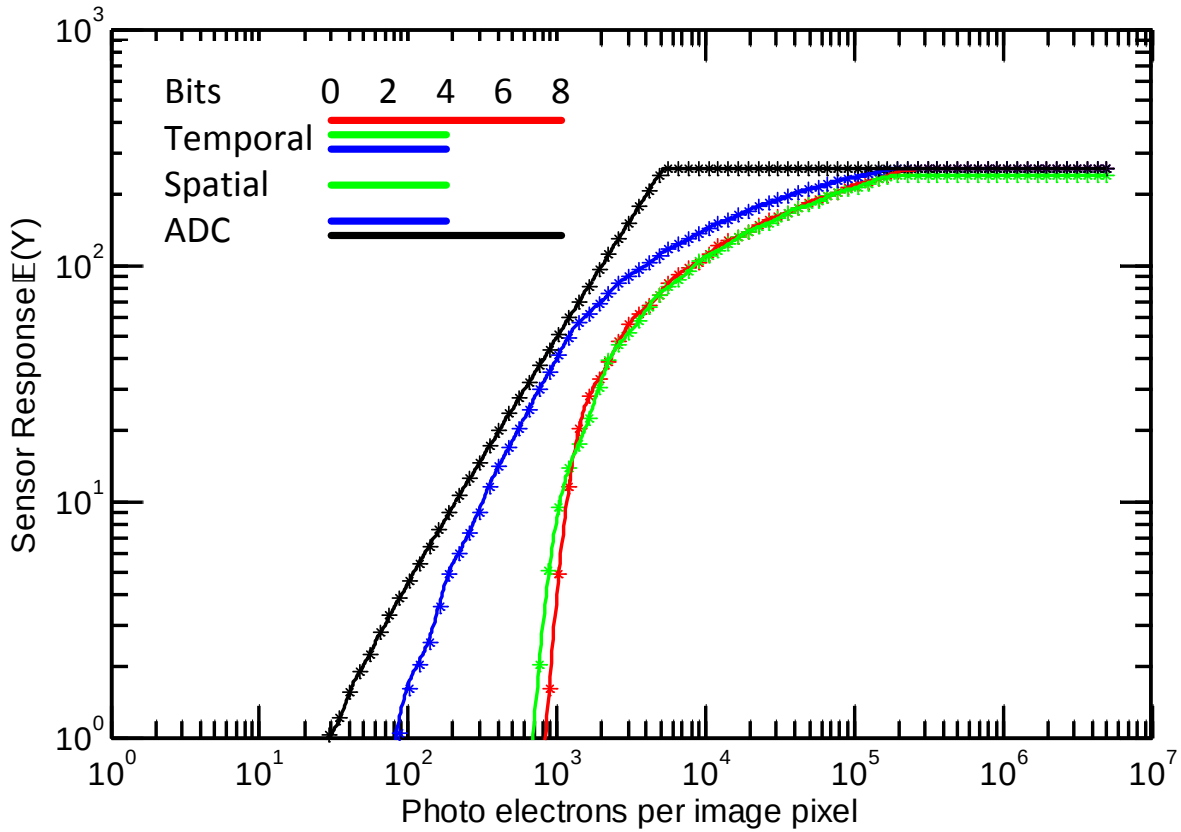
Example: pixel with 21 electrons full well capacity and 3-bit ADC

| Incident light (photons) | Threshold $\theta$ (photons) | Data number $d$ (output) | Probability of $\theta$ reached or exceeded | Probability to return $d$ |
|---|---|---|---|---|
| 21 and above | 21 | 7 | $P_7 = Pr[y \geq 21]$ | $P_7$ |
| 18 to 20 | 18 | 6 | $P_6 = Pr[y \geq 18]$ | $P_6 - P_7$ |
| 15 to 17 | 15 | 5 | $P_5 = Pr[y \geq 15]$ | $P_5 - P_6$ |
| 12 to 14 | 12 | 4 | $P_4 = Pr[y \geq 12]$ | $P_4 - P_5$ |
| 9 to 11 | 9 | 3 | $P_3 = Pr[y \geq 9]$ | $P_3 - P_4$ |
| 6 to 8 | 6 | 2 | $P_2 = Pr[y \geq 6]$ | $P_2 - P_3$ |
| 3 to 5 | 3 | 1 | $P_1 = Pr[y \geq 3]$ | $P_1 - P_2$ |
| 0 to 2 | | 0 | | |

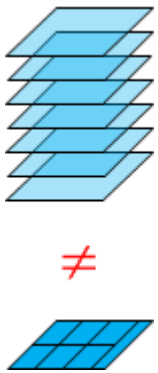
$$\text{Expected data number } =$$
$$1 \cdot (P_1 - P_2) + 2 \cdot (P_2 - P_3) + 3 \cdot (P_3 - P_4) + 4 \cdot (P_4 - P_5) + 5 \cdot (P_5 - P_6) + 6 \cdot (P_6 - P_7) + 7 \cdot P_7 =$$
$$P_1 + P_2 \cdot (2-1) + P_3 \cdot (3-2) + P_4 \cdot (4-3) + P_5 \cdot (5-4) + P_6 \cdot (6-5) + P_7 \cdot (7-6) =$$
$$P_1 + P_2 + P_3 + P_4 + P_5 + P_6 + P_7 =$$
$$\text{Response of spatially oversampled binary sensor}$$

- Multi-bit sampling is mathematically equivalent to binary oversampling with virtual jots having thresholds at the steps of the ADC

# Sensor Response: Unconditional Reset




multi-bit virtual jots




spatial real jots

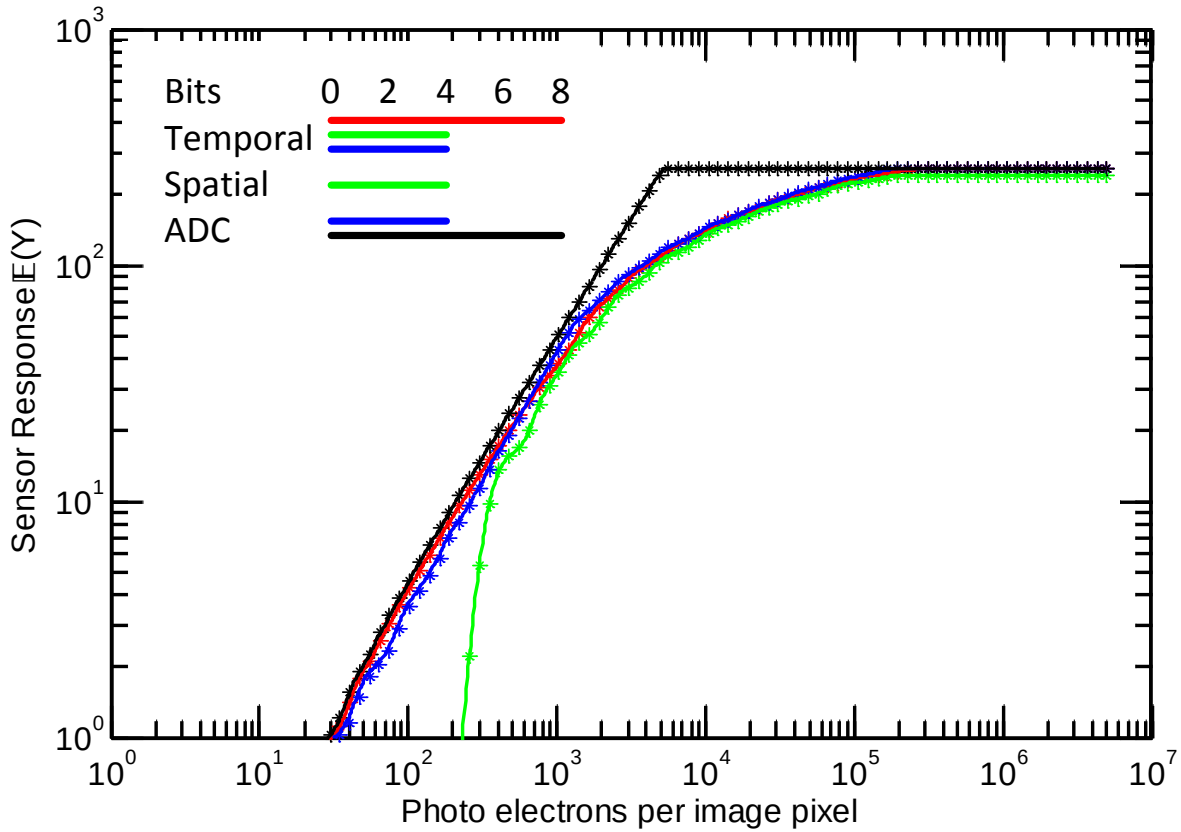
Threshold respectively ADC step size 20 electrons

Sampling interval duration from 1 to 128 for oversampled curves

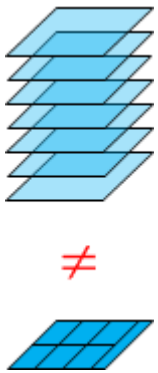
High light response extended by spatial and temporal oversampling

Low light response degraded by unconditional reset and spatial oversampling

# Sensor Response: Conditional Reset



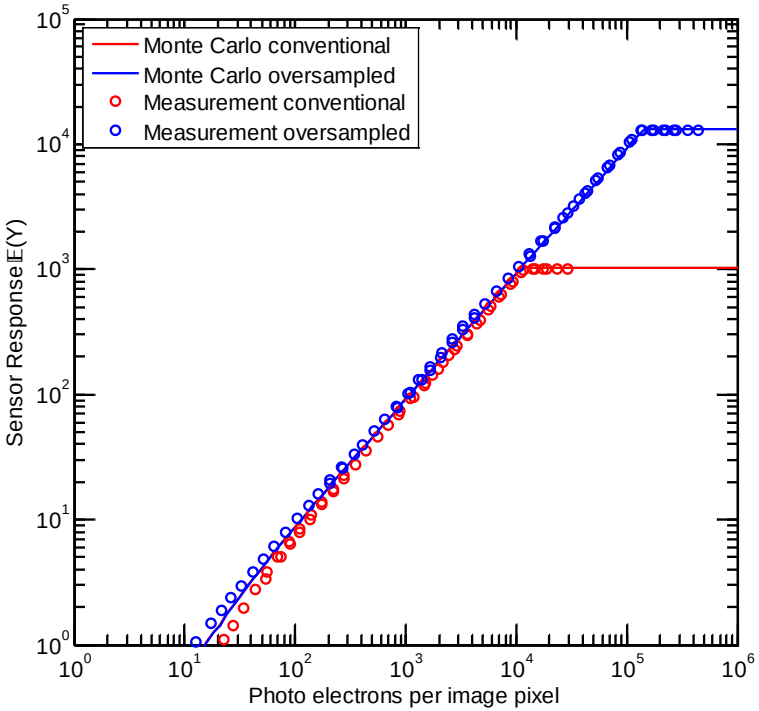

multi-bit virtual jots

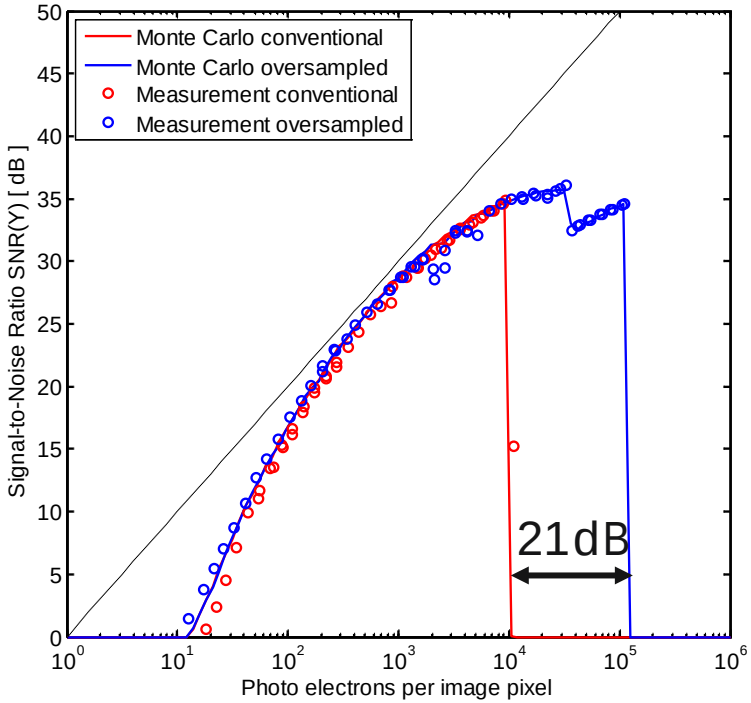



spatial real jots

Threshold respectively ADC step size 20 electrons
Sampling interval duration from 1 to 128 for oversampled curves
High light response extended by spatial and temporal oversampling
Low light response maintained by conditional reset

# Hardware Verification




- Results from small test chip (64·64 pixels) show excellent agreement between model and hardware
- 4T based pixel with correlated double sampling
- HDR function can be applied to all pixel sizes

# Conclusions

- Multi-bit oversampling with conditional reset makes the dynamic range benefits of binary pixel oversampling available in today's small pixel technology
- Poisson-statistics based modeling allows software prototyping of sensors
- The model has been experimentally verified on a small test chip
- The choice of sampling policy determines the sensor performance
  - Low end of dynamic range determined by pixel area and total exposure time
  - High end of dynamic range determined by jot area and duration of shortest sampling interval