Noise-Optimal Capture for High Dynamic Range Photography

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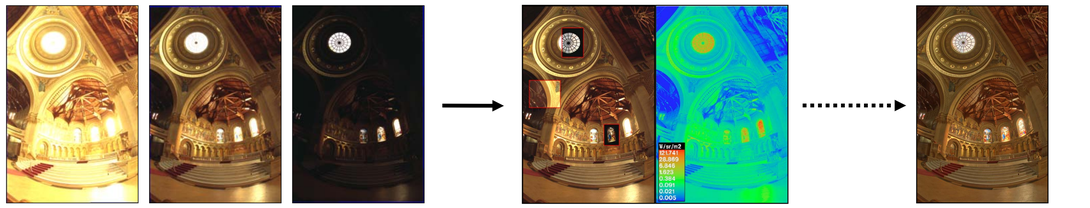
Multiple Exposures for High Dynamic Range



HDR capture → merged → tone mapped

effectively a method for per-pixel **noise reduction**

Goal: Capture photo of a subject in **given total exposure time**, with the **highest per-pixel SNR** over its dynamic range.
- number of shots?
- exposure time & ISO for each shot?

Key: Detailed Per-Pixel Noise Model

radiant power Φ → exposure time t → saturation → gain factor $g = k \cdot \mathrm{ISO}$ → raw pixel value I

photon noise $\sqrt{\Phi t}$ | read noise σ_{read} | ADC noise σ_{ADC}

linear image formation:

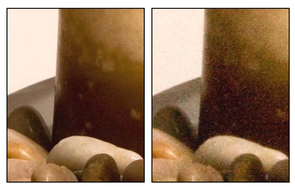
$$I = \min\left(\Phi t \cdot g + n,\ I_{\max}\right)$$

sensor noise (non-saturated pixel):

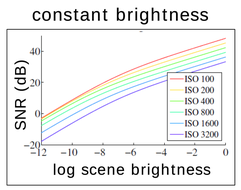
$$\mathrm{Var}(n) = \Phi t \cdot g^2 + \sigma_{\mathrm{read}}^2 \cdot g^2 + \sigma_{\mathrm{ADC}}^2$$

The High ISO Advantage

Conventional wisdom about ISO:



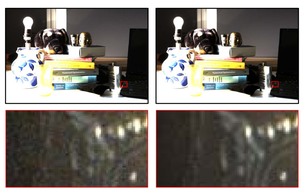
ISO 100, 1/10 sec | ISO 1600, 1/160 sec



exposure time / 16
gain × 16

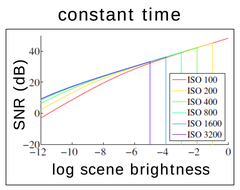
- "shoot the **lowest ISO possible**" that avoids motion blur [Bloch 07][McCollough 08]

ISO for a fixed exposure time:



ISO 100 1/200 sec **scaled × 32** | **ISO 3200** 1/200 sec

ADC noise negligible



- high ISO trades **lower dynamic range** for **higher SNR** (esp. in shadows)

Exploit **SNR** benefit of **high ISO** with multi-photo capture

Globally Optimal Capture Sequence

optimal HDR merge: [Kirk & Andersen 06]
- per-pixel MMSE blending weights $\propto t^2 g^2 \mathrm{Var}(n)^{-1}$
- SNR of optimal merge:

$$\mathrm{SNR}(\Phi)^2 = \sum_{i,j} m_{i,j} \cdot \frac{\Phi^2 t_i^2 \cdot \left[I_{i,j} < I_{\max}\right]}{\Phi t_i + \sigma_{\mathrm{read}}^2 + \sigma_{\mathrm{ADC}}^2 / g_j^2}$$

$m_{i,j}$: #photos per camera setting

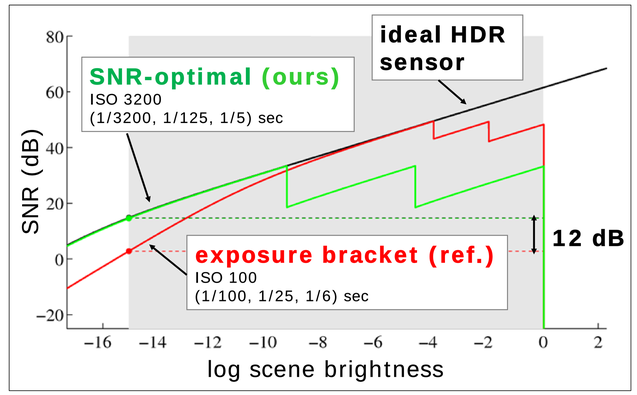
worst-case SNR:
- evaluate at finite #keypoints, K

mixed integer linear program (ILP):

$$\begin{aligned} &\text{maximize} && \mathrm{SNR}_{\mathrm{worst}}^2 \\ &\text{subject to} && \textstyle\sum_{i,j} m_{i,j}(t_i + t_{\mathrm{over}}) \le t_{\max} + t_{\mathrm{over}} \\ & && \mathrm{SNR}(\Phi)^2 \ge \mathrm{SNR}_{\mathrm{worst}}^2 \quad \text{for all } \Phi \in K \\ & && m_{i,j} \ge 0 \text{ and integer} \end{aligned}$$

→ **optimal capture sequence**

example SNR-optimal analysis:
- Canon 1D Mark III
- scene dynamic range = 33900 (15.1 stops)
- total exp. time ≤ 0.25 sec, max 3 photos
- **tractable:** ~0.5 sec runtime for ILP



Experimental Results

- Canon 1D Mark III
- scene dynamic range = 6500 (12.7 stops)
- total exp. time ≤ 87 msec, max 3 photos