Noise-Optimal Capture for High Dynamic Range Photography: Supplemental Materials

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A. Extended Image Formation Model

It is straightforward to extend our approach to incorporate thermal noise, due to the release of electrons from thermal energy the electronics. This effect can be modeled by the addition of *dark current*, D, to the radiant power from the scene (Fig. 1),

For a given temperature, thermal noise is largely systematic, so we assume that it can be calibrated on a per-pixel basis [13]. Thermal noise has a small effect for exposures below several seconds. For example, for the Canon 1D Mark II, the “hottest” pixels correspond to $D \approx 0.25$ electrons/s [7]. Modeling thermal noise may be beneficial for astrophotography, where exposures of several minutes or longer are common.

We express our extended image formation model as:

$$I = \min\{\, (\Phi + D)t/g + I_0 + n,\ I_{\max}\,\} \tag{15}$$

$$\mathrm{Var}(n) = (\Phi + D)t/g^2 + \sigma^2_{\mathrm{read}}/g^2 + \sigma^2_{\mathrm{ADC}} \ . \tag{16}$$

Under this new model, the squared SNR is

$$SNR(\Phi)^2 = \frac{\Phi^2 t^2 \cdot [I < \tilde{I}_{\max}(g)]}{(\Phi + D)t + \sigma^2_{\mathrm{read}} + \sigma^2_{\mathrm{ADC}} g^2} \ , \tag{17}$$

and Eq. (7) can be updated analogously. The minimum-variance unbiased estimator must also be updated to incorporate dark current:

$$\hat{\Phi} = \textstyle\sum_k w_k \cdot \big((I_k - I_0) g_{j(k)}/t_{i(k)} - D \big) \Big/ \textstyle\sum_k w_k \ . \tag{18}$$

The only remaining part of our method to update are the keypoints for pixel saturation, whose calculation must incorporate dark current as well:

$$\mathcal{K} = \{\Phi_{\min}, \Phi_{\max}\} \cup \big(\{ (I_{\max} - I_0) g_{j(k)}/t_{i(k)} - D + \varepsilon \} \ \cap \ [\Phi_{\min}, \Phi_{\max}] \big) \ . \tag{19}$$

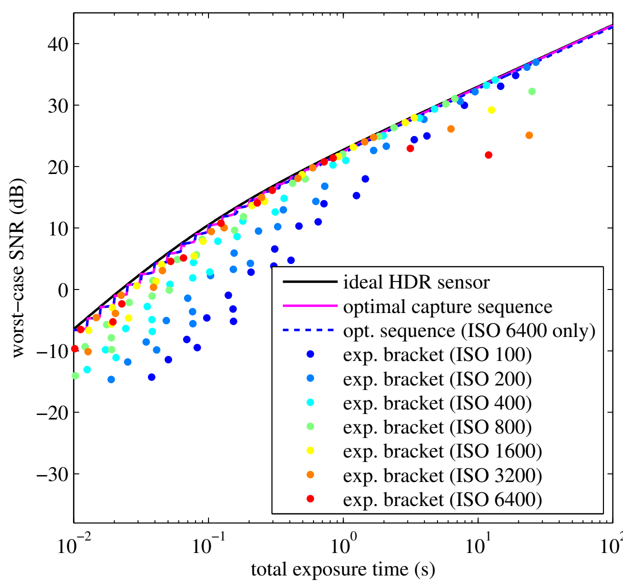

Figure 8. Worst-case SNR vs. total exposure time for the scene and camera in Fig. 5, assuming $t_{\mathrm{over}} = 0$. When ISO is fixed to its highest setting, ISO 6400, the performance of the optimal capture sequence (dotted blue) closely follows the optimal capture sequence when ISO is allowed to vary (magenta). We also plot all exposure bracketing sequences possible with this camera, captured with a range of fixed ISO settings (dots). The general trend is that the optimal ISO to use decreases with time budget.

B. Within-sequence ISO Variation

The results in Fig. 6 show that the bulk of our performance gains can be attributed to increasing ISO rather than adjusting exposure times. Another interesting question is the relative benefit of within-sequence ISO variation.

As Fig. 8 illustrates, sequences with high but constant ISO can still achieve near-optimal SNR, provided that the exposure times vary optimally and a large number of photos is allowed, *i.e.*, per-photo overhead time is low. Increasing ISO can be beneficial for standard exposure bracketing too. In this context, the optimal constant ISO is generally lower for longer time budgets, but this relationship is not monotonic.