Minimal-Bracketing Sets for High-Dynamic-Range Image Capture

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Abstract

- Proposed method
  - HDR image capture using LDR cameras
    - Three different minimal-bracketing algorithms
      - Computing minimum-sized exposure sets bracketing of HDR imaging
      - Amount of target scene irradiance
      - Acquisition of real time image
    - Two common types of HDR-imaging
      - Geometrical exposure setting
      - Arithmetical exposure setting
    - Experimental demonstration
      - Minimal-bracketing method
      - 1-stop bracketing method

Introduction

- Digital detectors problem
  - Large dynamic range in real world scene
  - HDR scene taken with LDR camera
    - Appearing noise at low irradiance in scene
    - Appearing saturated at high irradiance in scene
  - Solution method
    - Extending the dynamic range of LDR digital camera
      - Varying exposure of imaging system
  - Minimum number of exposure setting

Related work and paper contribution

- ◆ Requiring three step
  - – Capture and generation of HDR imaging
  - – Camera response function computation
    - Before capturing HDR scene
    - Defined as mapping between irradiance and recorded pixel value
      - – Multiple different exposure setting
      - – Recorded value of subset of image pixels

- LDR image acquisition and exposure variation
  - Capturing LDR image
    - Digital camera's shutter speed
    - Illumination variation
    - Split-aperture method
    - Statically varying exposure
    - Dynamically using programmable mask array
- HDR radiance map construction
  - Mapping relative irradiance value
    - Using inverse camera response function

◆ Contribution

- Reduced LDR image
- Control image of irradiance
- Using three algorithm minimum number of LDR
- Computing minimum bracketing set for HDR imageing
  - Geometric or arithmetic exposure control
- Experimental validation
  - Minimal bracketing
- Examining tradeoff
  - Between number LDR exposure and noise ratio of HDR radiance

Analytical framework and notation

◆ Defining exposure of HDR imaging system

$$Q \equiv E \bullet A \bullet t$$

Where Q **is average radiant energy**

E **is irradiance**

A **is detector area**

t **is exposure time**

– Controlled exposure of system
  - Shutter speed of camera
  - Aperture size of camera
  - External illumination on target scene

– Available exposure setting

$$Q = \{Q_0, Q_1, ..., Q_n\}$$

– Minimum and maximum scene irradiance

$$E_i^{\min} \quad , E_i^{\max}$$

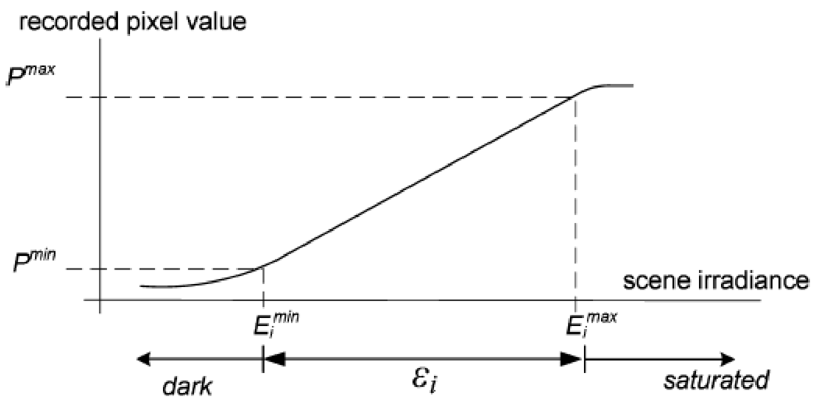
– Dynamic range

$$D_i = E_i^{\max} / E_i^{\min}$$

– Detectable range

$$\varepsilon_i \equiv [E_i^{\min}, E_i^{\max}]$$

Analytical framework and notation



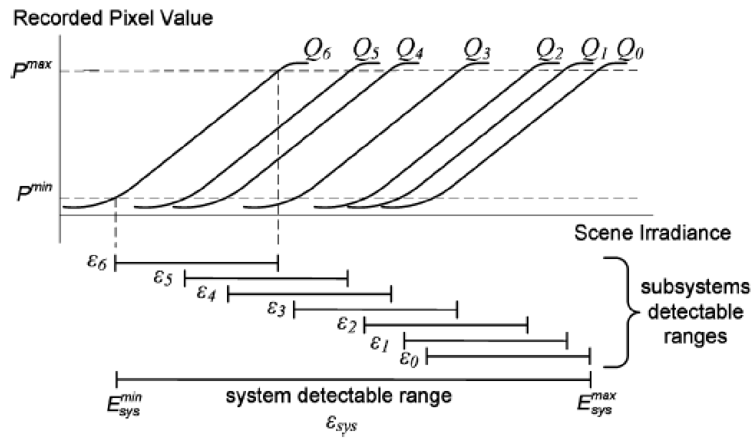


Fig.1. Response function of a digital camera determines how different levels of irradiance are mapped to pixel values at a given exposure setting. The detectable range of irradiance values at exposure setting is Q_i denoted by ε_i . Parts of the scene with irradiance values that fall outside of this range will appear dark or saturated in the corresponding LDR image.

Fig.2. Graphical representation of a HDR-imaging system. The overall detectable range of the HDR-imaging system ε_{sys} is obtained by taking the union if detectable ranges corresponding to each individual exposure setting

◆ Exposure variation types

- Geometric exposure variation
  - Constant factor larger than next lower setting
  - Using Shutter speed as means of varying exposure
  - Full stop or fraction of a stop
- Arithmetic exposure variance
  - Continued dynamic range
  - Using digital control signal
  - Relatively large of available exposure
  - Tightly packed set of available exposure

- Arbitrary exposure variable
  - Composite set of available exposure setting
    - Combination of illumination and shutter speed setting
    - Assuming 8bit illumination and 15-stop shutter speed
  - Arithmetic exposure varying system at low irradiance value
  - Geometrical exposure varying system at mid and high value
  -

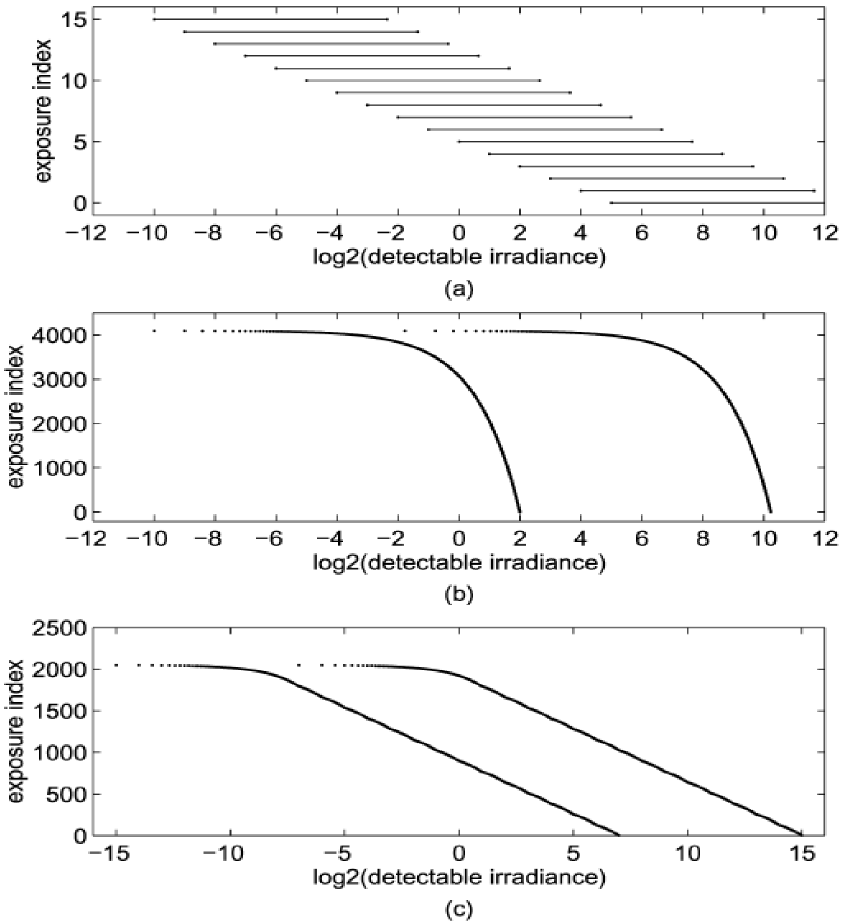


Fig.3. **system model for three HDR-imaging system with different types of available exposure settings. A geometric-exposure-set system and an arithmetic-exposure-set system are represented in (a) and (b), respectively. The model in (c) represents the set of detectable ranges for a system that combines (geometric) shutter-speed variation with (arithmetic) digital illumination control. Because of the large number of exposure available in the arithmetic and arbitrary systems, only the endpoints of each detectable range are shown.**

Minimal bracketing algorithm

- MIBS and MSBS
  - MIBS
    - Image bracketing set of minimal size
    - Using minimal number of LDR exposure
      - Complete capture
  - MSBS
    - System bracketing set of minimal size
    - Entire detectable range of HDR imaging system

◆ Minimal bracketing algorithm

– Blind acquisition

- No real time processing of image
- No prior knowledge of target scene range of irradiance value
- Contained MSBS in HDR imaging system
- Start at the lowest exposure setting
- Minimal overlap of previously added exposure setting
- Terminated adding the highest exposure setting
- Upward direction

$$M^u = \left\{ M_0^u, M_1^u, \ldots, M_m^u \right\}$$

- Downward direction

$$M^d = \left\{ M_0^d, M_1^d, \ldots, M_m^d \right\}$$

Input: Set of detectable ranges $\{\varepsilon_0, \varepsilon_1, \ldots \varepsilon_n\}$ ordered by decreasing right endpoints ε_i^{max} and corresponding set of exposure settings $\mathbf{Q} = \{Q_0, Q_1, \ldots Q_n\}$ of the HDR-imaging system

Output: Size of minimal-system-bracketing set $(m+1)$ and indices of exposures contained in greedy upward-direction MSB set $M^u = \{M_0^u, M_1^u, \ldots M_m^u\}$

Initialization:

(Add lowest exposure to solution)

1. $prev = 0$
2. $curr = prev + 1$
3. $m = 0$
4. $M_0^u = prev$

Iteration:

(Add exposure whose detectable range overlaps at least one exposure in solution set and that covers as much of remaining detectable range as possible)

```
5.  while curr ≤ n do
6.      next = curr
7.      while E_curr^max > E_prev^min and curr < n
8.          if E_curr^min < E_next^min
9.              next = curr
10.         curr = curr + 1
11.     m = m + 1
12.     M_m^u = next
13.     prev = next
```

Fig.4. Optimal greedy algorithm for finding the upward-direction minimal-system-bracketing set (MSBS) of a HDR-imaging system. The algorithm starts at the lowest exposures setting of the system and greedily adds exposure until it terminates after adding the highest exposures setting. For systems in which the subsystem dynamic range D_i is constant for all exposure, the condition at line 8 always evaluates to true, and the algorithm finds at each iteration, the exposure setting that has minimal overlap with that of the previously added exposure setting

– Clairvoyant acquisition

- Prior knowledge of target scene range of irradiance value
- Computing MIBS
  - Using simple greedy algorithm similar to MSBS algorithm

line 4, and line 6 with

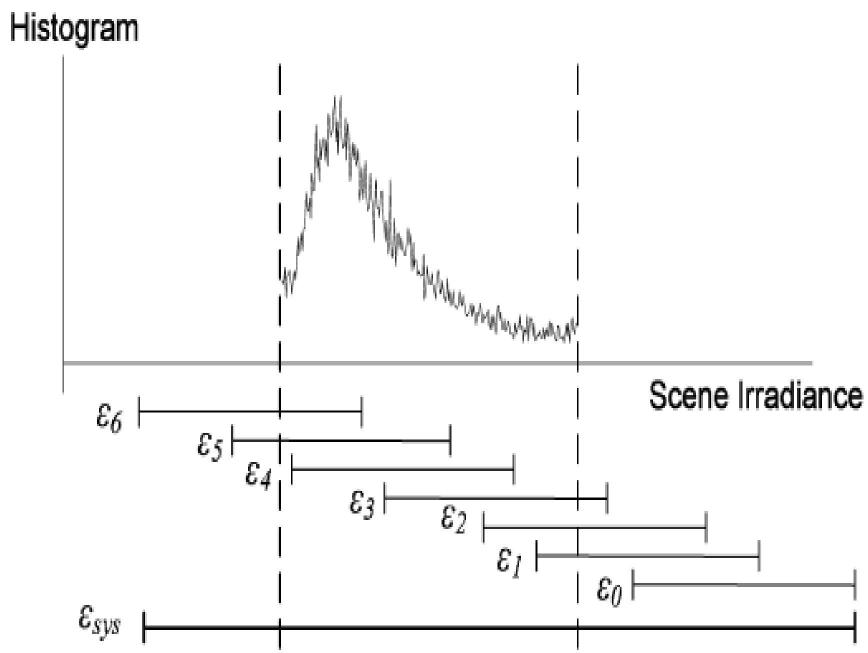
$$1.prev = \max\{j\ E_{im}^{\max} \in [E_j^{\min}, E_j^{\max}]\}$$

$$5.\textbf{while } E_{im}^{\min} < E_{\text{curr}}^{\min} \textbf{ and } curr \le n \textbf{ do}$$

$$7.\textbf{while } E_{\text{curr}}^{\max} > E_{\text{prev}}^{\min} \textbf{ and } E_{im}^{\min} < E_{\text{next}}^{\min}$$

$$\textbf{and } curr < n \textbf{ do}$$

– Blind acquisition with feedback
  - Based nearly minimal image bracket algorithm
  - No prior scene irradiance information
  - Start by acquiring image at central exposure setting
  - Captured in resulting LDR image
  - Automatical termination



minimal system bracketing set = $\{Q_0, Q_2, Q_4, Q_6\}$

minimal image bracketing set = $\{Q_3, Q_5\}$

feedback-based bracketing set = $\{Q_2, Q_4, Q_6\}$

Fig.5. Histogram of a target scene's irradiance and the system model of a HDR-imaging system are shown. Having no prior information about the target scene's irradiance range, the feedback-based-bracketing procedure presented in Section IV-C selects a central staring exposure Q_4, which results in a bracketing set containing three exposure $\{Q_2, Q_4, Q_6\}$. The minimal-image-bracketing set, by contrast, contains only two exposure $\{Q_3, Q_5\}$. For situations in which no target-scene irradiance information is available, one can guarantee that the scene is captured by using a minimal-system-bracketing set $\{Q_0, Q_2, Q_4, Q_6\}$.

Optimality results

- Presented greedy MSBS and MIBS algorithm
  - Optimality of MSBS algorithm
    - Minimum sized system bracketing sets for HDR imaging system
  - Optimality of MIBS algorithm
    - Minimum sized system bracketing sets for target HDR scene

Analytical results

◆ Expression for computing number of exposure

– Geometric exposure set system

- Expressed in term of HDR system highest detectable irradiance

$$E_i^{\max} = (C_g)^{-i} E_{sys}^{\max} \quad , \qquad 0 \le i \le n \qquad \textbf{(1)}$$

Where, C_g **is constant ration between adjacent exposure setting and** D

D **is dynamic range of the LDR subsystems.**

– Minimal system bracketing sets

- Computed geometrically varying exposure system

$$m+1=\left\lceil \frac{n}{\left\lfloor \frac{\log D}{\log C_g} \right\rfloor} \right\rceil +1 \qquad (2)$$

- Upward and downward direction greedy MSBS

$$M_i^u = \begin{cases} i \bullet \left\lfloor \frac{\log D}{\log C_g} \right\rfloor & 0 \le i < m \\ n & i = m \end{cases} \qquad (3)$$

$$M_i^d = \begin{cases} n - i \bullet \left\lfloor \frac{\log D}{\log C_g} \right\rfloor & 0 \le i < m \\ 0 & i = m \end{cases} \qquad (4)$$

Where, $\lfloor \bullet \rfloor$ **and** $\lceil \bullet \rceil$ **denote the largest integers less than** $(\bullet)$ **and the smallest integer greater than** $(\bullet)$ **.**

– Minimal image bracketing sets

$$\left\lceil \log(D^{im}) / \log(D) \right\rceil$$

Where, $D^{im} \equiv E_{im}^{\max} / E_{im}^{\min}$ **is the dynamic range of the target scene.**

$$m = \left\lceil \frac{\dfrac{\log(\frac{E_{sys}^{\max}}{E_{im}^{\min} D})}{\log(C_g)} - \left\lfloor \dfrac{\log(\frac{E_{sys}^{\max}}{E_{im}^{\max}})}{\log(C_g)} \right\rfloor}{\left\lfloor \dfrac{\log D}{\log C_g} \right\rfloor} \right\rceil \quad \textbf{(5)}$$

$$M_i^u = \left\lfloor \frac{\log(\frac{E_{sys}^{\max}}{E_{im}^{\min}})}{\log(C_g)} \right\rfloor + i \left\lfloor \frac{\log(D)}{\log(C_g)} \right\rfloor \qquad 0 \le i \le m \quad \textbf{(6)}$$

$$M_i^d = \left\lfloor \frac{\log(\frac{E_{sys}^{\max} D_{im}}{E_{im}^{\min} D})}{\log(C_g)} \right\rfloor - i \left\lfloor \frac{\log(D)}{\log(C_g)} \right\rfloor \qquad 0 \le i \le m \quad \textbf{(7)}$$

– Arithmetic exposure set systems

- Expressed in term of HDR system highest detectable irradiance

$$Q = \{0, C_a, 2C_a, ..., nC_a\}$$

Where, C_a is a positive constant

$$E_i^{\max} = \frac{E_{sys}^{\max}}{i} \qquad 0 \le i \le n \qquad \textbf{(8)}$$

– Minimal system bracketing sets

- Upward and downward direction greedy MSBS

$$M_i^u = \underbrace{\left\lfloor \dots \left\lfloor \left\lfloor D \right\rfloor D \right\rfloor \dots D \right\rfloor}_{iD's} \qquad 0 \le i < m \qquad \textbf{(9)}$$

$$M_i^d = \underbrace{\left\lceil \dots \left\lceil \left\lceil \frac{E_{sys}^{\max}}{E} D^{-1} \right\rceil D^{-1} \right\rceil \dots D^{-1} \right\rceil}_{iD's} \qquad 0 \le i < m \qquad \textbf{(10)}$$

$$\left\lceil \frac{\log(n)}{\log(D)} \right\rceil \le m < \left\lceil \frac{\log(n)}{\log(D-1)} \right\rceil \approx \left\lceil \frac{\log(n)}{\log(D)} \right\rceil + 1 \qquad \textbf{(11)}$$

– Minimal image bracketing sets

$$M_i^u = \underbrace{\left\lfloor \cdots \left\lfloor \left\lfloor \frac{E_{sys}^{\max}}{E_{im}^{\max}} \right\rfloor D \right\rfloor \ldots D \right\rfloor}_{iD's} \qquad 0 \le i < m \qquad \textbf{(12)}$$

$$M_i^d = \underbrace{\left\lceil \cdots \left\lceil \left\lceil \frac{E_{sys}^{\max}}{E_{im}^{\max}} D^{-1} \right\rceil D^{-1} \right\rceil \ldots D^{-1} \right\rceil}_{iD's} \qquad 0 \le i < m \qquad \textbf{(13)}$$

$$\left\lceil \frac{\log(D_{im})}{\log(D)} \right\rceil \le m \le \left\lceil \frac{\log(D_{im})}{\log(D-1)} \right\rceil \approx \left\lceil \frac{\log(D_{im})}{\log(D)} \right\rceil + 1 \qquad \textbf{(14)}$$

Experimental results and discussion

- Experimental validation of MSBS for HDR image
  - System description and calibration
    - Acquiring LDR image at HDR radiance map
    - Combined weighted average for radiance value
    - Weighting function equaled to exposure time
  - Minimal bracketing and 1-stop bracketing results
  - Bracketing set density versus SNR tradeoff

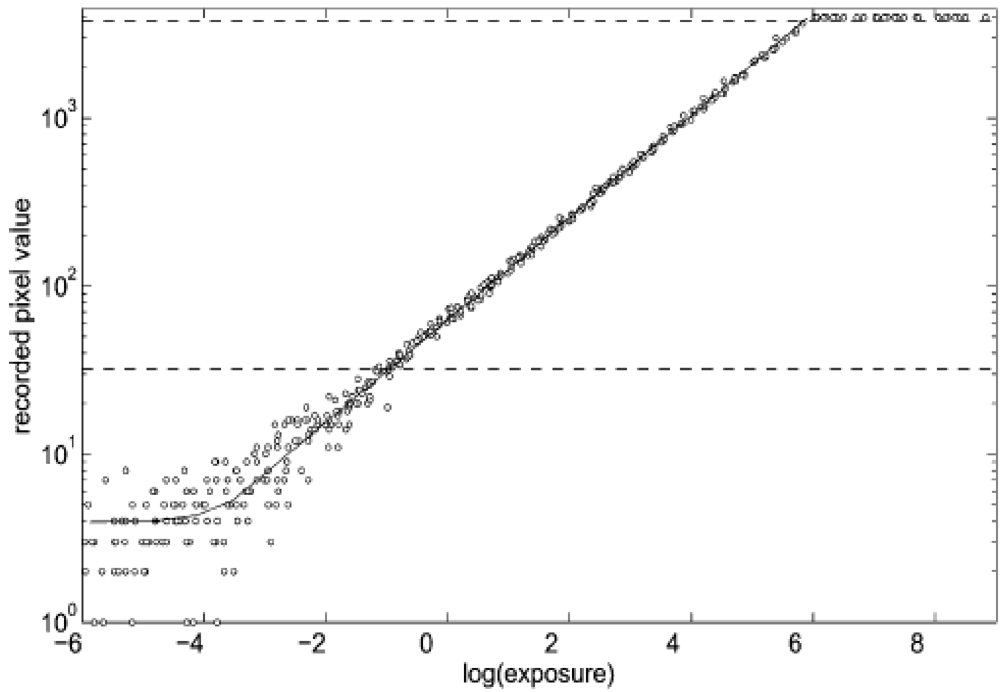


Fig.6. **Experimentally determined response function of Pentax *ist DS digital camera used for the experiments.**

Fig.7. **Using the feedback-based algorithm in Section IV-C, exposures at shutter speeds of 1/45s, and 1/4096s were captured (in that order). The resulting LDR images set is shown on the left of this figure. On the right of each LDR image is shown a map of the captured pixels for each image. Captured pixels are shown white, pixels that were either in saturation or below the system noise floor are shown in back.**

Table 1 Experimental results

scene	dynamic range	# of bracketing exposures	
		minimal	full-stop
1. office	$1.17 \cdot 10^5$	3	11
2. totem	$5.51 \cdot 10^3$	2	7
3. coffee	$5.61 \cdot 10^4$	3	10
4. exit	$2.47 \cdot 10^4$	3	9
5. classroom	$2.16 \cdot 10^4$	3	9

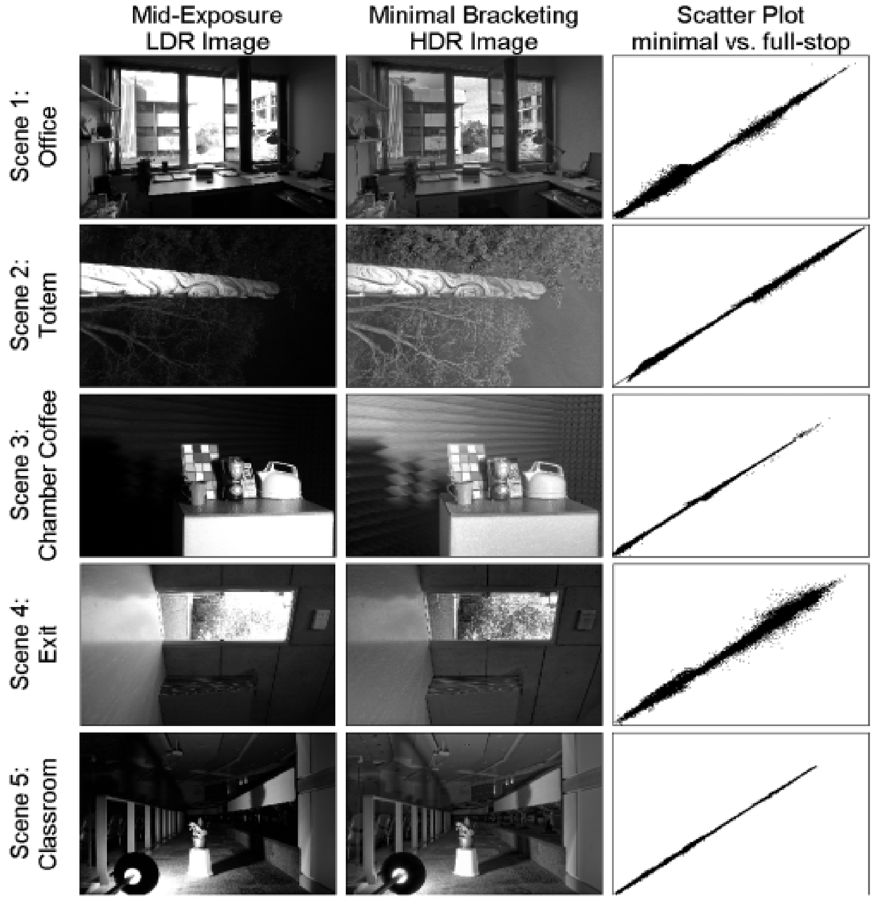


Fig.8. Five captured HDR scenes are shown here. The left column contains LDR images obtained at central exposure setting for each scene. Due to the limited dynamic range of the camera detector, each image has regions in saturation and regions in darkness. This is not the case for the images in the seconds column, which are tone-mapped versions of the HDR radiance maps obtained from the feedback-based minimal-bracketing procedure presented. The third column contains scatter plots comparing the pixel values in the 1-stop-bracketing and the minimal-bracketing radiance maps.

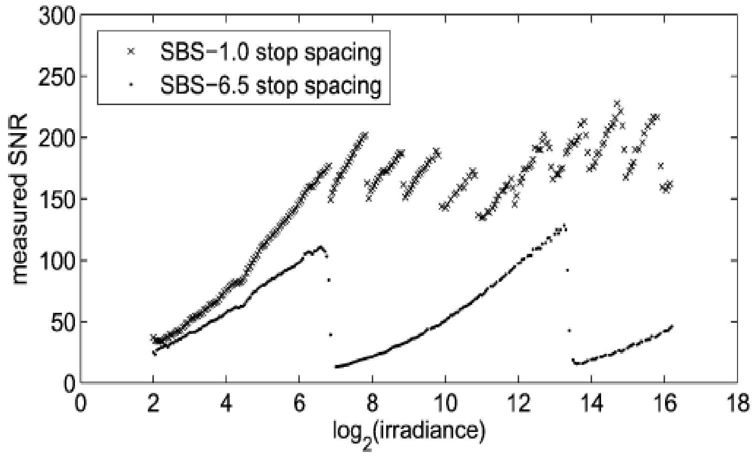


Fig.9. **SNR versus irradiance value for HDR radiance maps of the classroom scene shown in Fig.8. capture using obtained using minimal-bracketing and using 1-stop bracketing. 1-stop bracketing results in improved SNR, particularly for pixels recorded at low radiant energy in the minimal-image-bracketing set.**

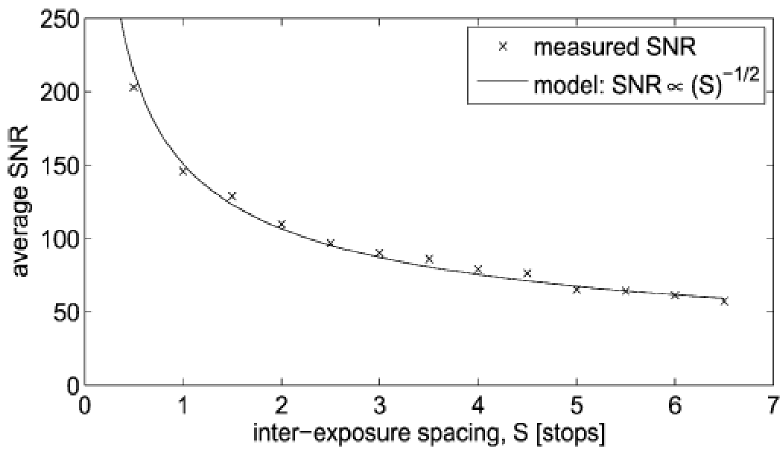


Fig.10. **SNR of the final computed radiance map averaged over the entire image as a function of the spacing between consecutive exposures in the image-bracketing set. Lower spacing results in each pixel being sampled a larger number of times, so the average SNR decreases as the spacing size increase.**

Summary

- Minimal bracketing methods
  - Reducing number of LDR image
  - Required average 30%as 1-stop bracketing
  - Best suited for qualitative HDR imaging