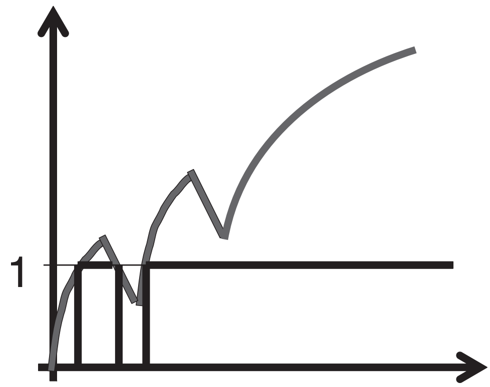

Figure 2.21 Dynamic range gap presence function.

2.6 Dynamic Range

2.6.1 Definition

Dynamic range is then defined by

$$DR = \frac{DR_{Hi}}{DR_{Lo}} \quad \text{or} \quad DR[dB] = 20 \log \frac{DR_{Hi}}{DR_{Lo}}. \tag{2.16}$$

2.6.2 Remark

Dynamic range can be misleading in data sheets. Some data sheets report dynamic range as a typical value for one configuration; other data sheets report the maximum intraframe dynamic range, which is the maximum reachable dynamic range among all possible configurations; other data sheets report a reasonable value for dynamic range that is reached by most sensor configurations; and some data sheets report a purely hypothetical value.

For example, one of the XDR CMOS image sensors available on the market has approximately 60 dB of dynamic range in linear mode, 154 dB of maximum intrascene dynamic range, around 180 dB of maximum reachable dynamic range over several images, and 130 dB of dynamic range in most reasonable configurations.

When working with sensor and camera dynamic range, it is important to always check the formula definition and the measurement conditions. When working with cameras, it is important to check if the published dynamic range refers to the sensor or to the camera, because the camera's dynamic range is reduced by optical veiling glare. It is surprising to see that some cameras are not painted in black or anodized inside their lens mounts, making them possible sources of reflections.

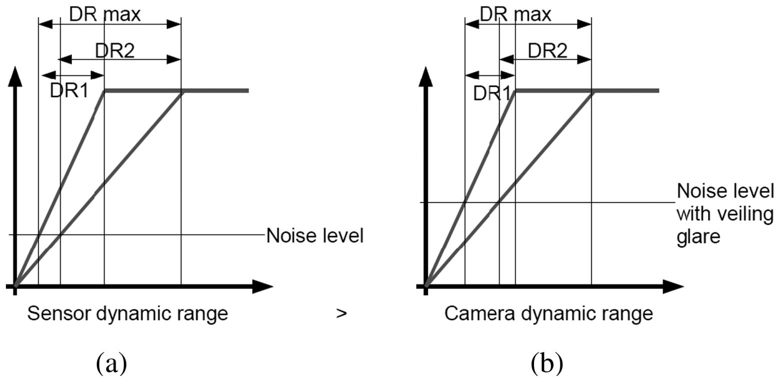

Figure 2.22 (a) Dynamic range of a sensor for short exposure time (DR2) and long exposure time (DR1), and the sensor's maximum reachable dynamic range (DR max); (b) dynamic range of a camera for short exposure time (DR2) and long exposure time (DR1), and the camera's maximum reachable dynamic range (DR max).

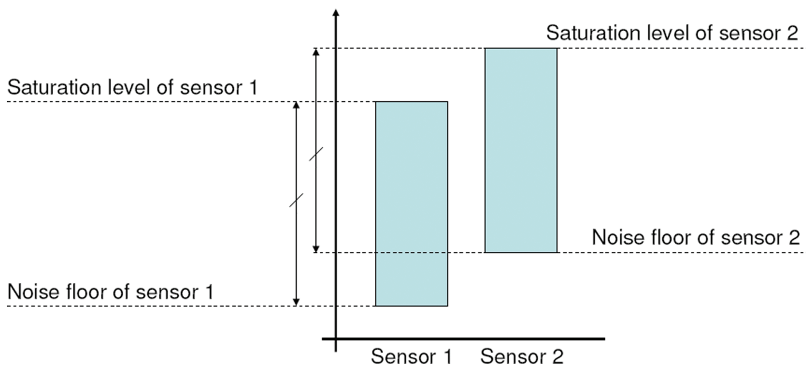

Figure 2.23 Dynamic range is a relative measurement (logarithmic vertical axis).

2.6.3 Relative measurement

Dynamic range is a relative measurement between a saturation level and a noise floor:

$$DR_{Hi,2} = \alpha DR_{Hi,1} \Longleftrightarrow \log DR_{Hi,2} = \log\alpha + \log DR_{Hi,1}, \tag{2.17}$$

and similarly for the lowest bound.

$$\log DR = \log \frac{DR_{Hi,2}}{DR_{Lo,2}} = \log \frac{\alpha DR_{Hi,1}}{\alpha DR_{Lo,1}} = \log \frac{DR_{Hi,1}}{DR_{Lo,1}}. \tag{2.18}$$

Scaling both elements will always yield the same dynamic range. As discussed earlier, there is a trade-off between performance in the dark areas and performance in bright areas, hence the need for parameter scaling.

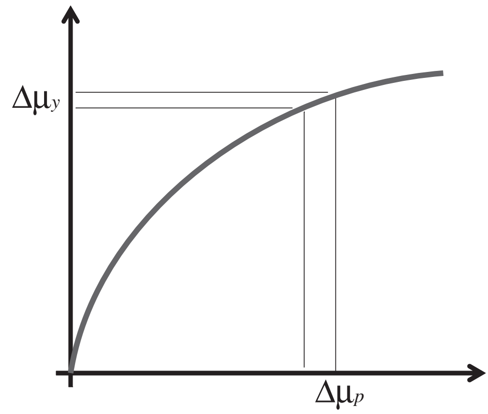

Figure 2.24 Relationship between irradiance variation and sensor output variation.

2.7 Image Information

The incremental gain defined above is a measurement of the amount of information that is transferred from the scene into the image. When the incremental gain is high, a small variation of luminance results in a large variation of the sensor's output, which means that a lot of details, i.e., a lot of information, are transferred from the scene into the image. When the incremental gain is low, a small variation of luminance results in almost no variation of the sensor's output, which means that almost no details, i.e., almost no information, are transferred from the scene into the image. When a dynamic range gap is present, there is no information at all transferred from the scene into the image.

The function

$$I(\mu_p) = g(\mu_p) \cdot \mathrm{DRG}(\mu_p) \tag{2.19}$$

is a representation of the amount of information that can be transferred between the scene and the image, and is called the information transfer function. If

$$I(\mu_p) = \frac{d\mu_y}{d\mu_p} \cdot \mathrm{DRG}(\mu_p) \approx \frac{\Delta\mu_y}{\Delta\mu_p} \cdot \mathrm{DRG}(\mu_p) < \frac{ADC_{step}}{\Delta\mu_p}, \tag{2.20}$$

then no information can be retrieved from the variations in a scene smaller than $\Delta\mu_p$. (Due to noise, if several images are averaged to obtain a floating point representation of the pixel value, it is possible to obtain information from an irradiance variation of less than $\Delta\mu_p$.)

A noiseless linear sensor operating on the same ADC would transfer at most (if the dynamic range gap close to total dark is ignored) an information quantity of

$$I_{linear}(\mu_p) = \frac{ADC_{Range}}{DR_{Hi}}. \tag{2.21}$$

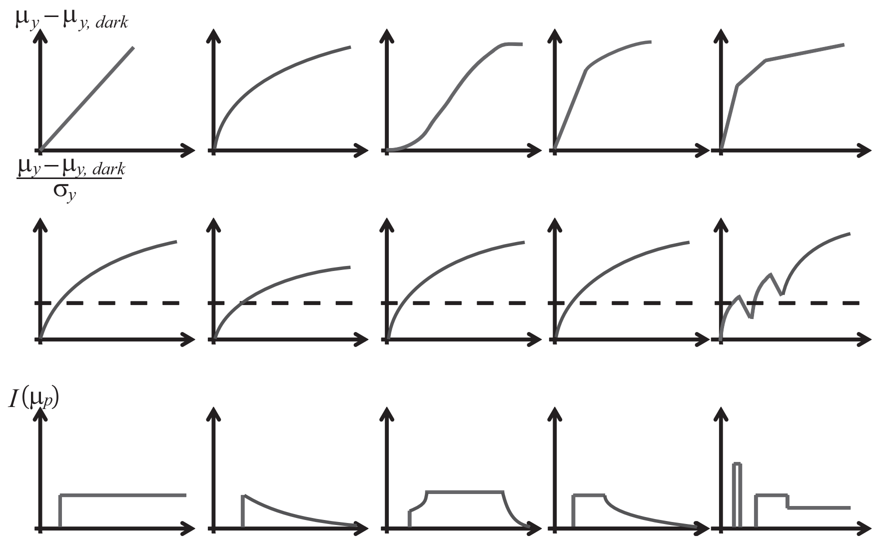

Figure 2.25 Information transfer functions for several sensor-response curves.

One can compare the information transfer of any sensor to this ideal linear sensor using the information gathering ratio, defined as

$$i = \frac{I}{I_{linear}}, \tag{2.22}$$

or its average:

$$\bar{i} = \frac{\frac{1}{DR_{Hi}} \int_0^{DR_{Hi}} I(\mu_p) d\mu_p}{\frac{ADC_{Range}}{DR_{Hi}}} = \frac{1}{ADC_{Range}} \int_0^{DR_{Hi}} I(\mu_p)\, d\mu_p, \tag{2.23}$$

where the DR_{Hi} value is the same for the XDR and the linear sensors.

Figure 2.25 shows examples of information transfer functions for several sensor response curves [remember that $(d/dx)\log_a(x) = 1/(x \ln a)$]. There is no information transferred when $SNR < 1$ (dynamic range gaps) and the information transfer is proportional to the derivative of the response curve, where $SNR \geq 1$.

2.8 Human Vision System and Its Dynamic Range

Human vision is not covered in detail here due to its extreme complexity. However, it is important to understand that the eye behaves very differently compared to a camera, and the human eye, if not an ideal sensor, is only a good image sensor that is familiar to us.

2.8.1 General properties of human vision

Rods are present in large quantities across the entire surface of the retina (wide field of view). They have high sensitivity but a low resolution. Vision based on rods is called scotopic, and the spectral response is called the scotopic curve.

Cones have a significantly lower sensitivity but higher resolution (it is said that their resolution is comparable to a 10-megapixel sensor). They are more sparsely populated in the periphery, and most are found around the center of the complete field of view of the rods. Vision based on cones is called photopic, and the spectral response is called the photopic curve.

Cones exist in three types, each sensitive to a different part of the spectrum: red, green, and blue. This limitation to three spectral bands produces a phenomenon called metamerism, whereby a pair of spectrally different specimens match under one illuminant but not under other illuminants. Because of the limited spectral detectors available in the human eye due to a color space limitation of the human eye, metamerism can occur. Some animal species have more-advanced multispectral-imaging systems, as some sensors do.

The human eye has greater sensitivity to relative luminance levels than to absolute levels and has a nonlinear relationship between luminance and subjective brightness perception (demonstrated on incremental thresholds by the Weber–Fechner logarithmic law). The visibility threshold often increases in the vicinity of edges; this effect is sometimes called sensitivity masking.

2.8.2 Dynamic range of the human eye

It is often stated that the human vision system has a large dynamic range of around 120 dB. However, there is confusion between the intrascene dynamic range and the maximum dynamic range. In the presence of bright light, the eye has difficulty seeing details in the shadows and its dynamic range is about 40 dB. In the dark, the eyes need time to adapt before they can see reasonably well. There is a large ratio between the bright objects that the eyes can see in bright sun and the dark scenes that it can see in the dark after adaptation, but it won't be able to see both levels in the same scene.

The retina has a contrast ratio of around 100:1 (40 dB, maximum intrascene dynamic range*). Initial dark adaptation can take place in about four seconds; complete dark adaptation caused by the regeneration of rhodospin in rods takes place in about 30 minutes but can be affected by tobacco or alcohol. This process allows the human eye to reach a total dynamic range of about 1000000:1 (120 dB, maximum reachable dynamic range across multiple scenes). This adaptation to light is independent of the adaptation of the pupil.

2.8.3 Noise perception

In a still image, the random noise becomes FPN because it is just one sample of the temporal noise. For video, random noise is usually averaged by human vision

*Other phenomena, adaptations to the scene and brain processing can improve this value.

and is less critical. Correlated noises (noises that form a regular repeated spatial or temporal structure) are usually more easily noticed than purely random noises. Random temporal noise is assumed invisible if the SNR is higher than 30 dB.

2.8.4 Optical performance

The human eye has the ideal advantage of a curved sensor (the retina), simplifying optical design: a very simple optical system can project images nearly distortion-free on the sensing plane.