5. FRAME CAMERAS

A frame camera is a camera which allows all parts of the image frame to be imaged simultaneously. This is the format of most film cameras and is the characteristic format of standard digital cameras. The optical characteristics of digital and photographic cameras are in all essential aspects. In many ways this is the simplest form of an imaging system since there is minimal motion and the geometry of the image frame is well defined.

5.1 Radiation as "Exposure"

In a frame camera the entire imaging surface (whether film or 2-dimensional digital array) he data is exposed simultaneously. Basically, the photosensitive material in the camera is exposed to light (i.e., radiation) which is reflected or scattered into the field-of-view of the camera lens. When the camera shutter is open, light passes through the lens and reaches the photosensitive material. Radiation from any object in the scene imaged is thus recorded as "exposure" -- the intensity of light which reaches the photographic material, multiplied by the duration of the light.

\[
\text{For a vertical image (nadir viewing):} \\
\text{FOV @ aperture} = 2 \tan(\theta_{\text{FOV}} / 2) \\
\Omega_s = A_s / H^2 \sec^2 \theta = \text{angle subtended by a source element at a distance } R \sec \theta \\
\Omega_a = A_a / H^2 \sec^2 \theta = \text{angle subtended by a camera aperture at a distance } R \sec \theta \\
\text{Radiance} \quad [\text{watts/m}^2\text{-ster.}] \\
\frac{dL}{dA d\Omega_s} = \frac{d^3P}{dA d\Omega_s}
\]

**Figure 5.1:** Geometry of radiance at a camera aperture.

Radiance at the camera aperture from a single source within the field of view of the camera is the radiant flux (power) received from a source with area \( A_a \) that subtends at a distance \( H \sec \theta \). Here, \( \theta \) is the angle between the camera axis and the line between the camera aperture and the source (Figure 5.1). Radiance at the aperture from a source element is given by:

In words, the radiance at the camera aperture is given by the power per unit area of the source element emitted into the solid angle subtended by the aperture. Alternatively, the radiance at the aperture is the power per unit area of the aperture incident on the aperture from the solid angle subtended by the source element.

Radiance from the source element is altered (attenuated) by scattering and absorption when passing through the atmosphere. Light is also scattered into the view of the sensor (path radiance,
Thus, the radiance at the aperture from the viewing direction, $L_a(\theta)$, is related to the radiance leaving the surface element, $L_s(\theta)$, by:

$$L_a(\theta) = \frac{P}{A_s \Omega_s} = \frac{P}{\Omega_s H^2 \sec(\theta) \frac{A_a}{H^2 \sec(\theta)}} = \frac{P}{A_s \Omega_s}$$

(5.1)

In words, the radiance at the camera aperture is given by the power per unit area of the source element emitted into the solid angle subtended by the aperture. Alternatively, the radiance at the aperture is the power per unit area of the aperture incident on the aperture from the solid angle subtended by the source element.

Radiance from the source element is altered (attenuated) by scattering and absorption when passing through the atmosphere. Light is also scattered into the view of the sensor (path radiance, $L^*$). Thus, the radiance at the aperture from the viewing direction, $L_a(\theta)$, is related to the radiance leaving the surface element, $L_s(\theta)$, by:

$$L_a(\theta) = L_s(\theta) \tau + L^*(\theta)$$

(5.2)

where $\tau$ is the attenuation factor, the proportion of the radiance removed by scattering and absorption in the atmosphere, and $L^*$ is the path radiance, the sunlight and skylight scattered into the viewing path.

The radiance at the detector from the viewing direction, $L_d(\theta')$, is further reduced by transmission through the camera optics (including filters), i.e.,

$$L_d(\theta') = (L_a(\theta) \tau + L^*(\theta)) \tau_o$$

(5.3)

where: \( \tau_o = \) optical transmission factor

Finally, irradiance at a point on the detector illuminated by radiance, $L_d(\theta')$, is given by:

$$E_d = L_d(\theta')\Omega_s = (L_s(\theta) \tau + L^*(\theta)) \tau_o \Omega_s$$

(5.4)

Irradiance is the fundamental quantity of direct interest whether working with a solid state detector or film or any other detector. It represents the power per unit area on the detecting surface. Since the purpose of most frame cameras is to produce a visual image, exposure is usually defined in photometric rather than radiometric units. The duration of exposure is normally stated in seconds, and the intensity of the exposure is stated in lumens/meters², lux, or meter-candles. Since 1 lumen/meter² = 1 lux = 1 meter-candle, then photographic exposure could be described as lumen-seconds/meter², or lux-seconds, or meter-candle seconds. The last is the easiest to visualize (no pun intended): the amount of light a candle gives off in one second at a distance of one meter. It is emphasized that this photometric measure of energy is analogous to the radiant measure of energy described in Sections 2.3 and 5.2 (i.e., irradiance multiplied by time).

### 5.2 Photographic Materials and Processing

The photographic material consists of an emulsion coated on a base (Figure 5.2). The emulsion is normally composed of silver halide crystals suspended in gelatin, and the base may be paper, film or glass. A radiation-absorbing layer is commonly applied to the back of the emulsion base to suppress halation, the spreading of a photographic image beyond its proper boundaries (i.e., image "halos," especially around bright objects). Halation is caused primarily by incoming
radiation that passes through the emulsion, reflects from the backside of the emulsion base, and then interacts with the halide crystals.

![Cross-section of photographic material](image)

**Figure 5.2:** Cross-section of photographic material

In the general case, when a photographic material is exposed to radiation from a scene, an invisible latent image of the scene is formed in the halide crystals in the emulsion. In order that the latent image can be made visible, the exposed crystals must be developed; in order that the visible image can be retained, the emulsion must then be fixed and washed.

Placing an exposed photographic material in an appropriate developing solution, allows the chemicals of the developer to react with the silver halide crystals which "contain" the latent image, freeing and depositing microscopic grains of metallic silver. The density of these silver deposits corresponds to tone of the image; the denser the silver deposition the negative, the brighter the image on the positive.

Density (D) is measured as the logarithm of the inverse of the fraction of light transmission (T) through the photographic product: \( D = \log \left( \frac{1}{T} \right) \). For example, if a film transmits 100% of the light, its density is \( \log \left( \frac{1}{1.00} \right) = 0 \). With a transmission of 10%, density is \( \log \left( \frac{1}{0.10} \right) = 1.0 \), and with a transmission of 1%, density is 2.0 (Figure 5.3).

![Exposure vs Density Chart](image)

**Figure 5.3:** Relationship between exposure, transmission and density.

Although the developer also reacts with the unexposed silver halide crystals, this reaction is much slower. Only small amounts of silver will be deposited in the unexposed areas of the emulsion during the normal time of development ("fog density"). Further, when the desired degree of development is obtained, the photographic material is immersed in a stop bath to end all development reactions.

After development, the undeveloped silver halide crystals must be removed from the emulsion because they would darken upon exposure to light. This is accomplished by immersing the developed photograph in a fixing bath. The chemicals of the fixer, or "hypo", form a soluble compound with the undeveloped halide crystals but have virtually no effect on the developed image.
The chemicals and dissolved silver compounds must then be washed out to prevent their fading and staining the image. As such, the final steps in photographic processing are washing, the basic agent being water, and drying.

These procedures apply to the processing of negatives or positives. Given a negative transparency, a positive print or transparency can be obtained by exposing sensitized photographic paper or film to light which passes through the negative (e.g., in an enlarger or contact printer). The exposed photographic material is then developed, fixed, washed and dried, as described.

Using a somewhat different process, it is possible to obtain a positive without first having to produce a negative. The process is called "reversal", and its primary application in remote sensing is for color and color infrared aerial films. Reversal processing has several variations depending, in part, on the specific photographic emulsion. The easiest to consider is as follows: in negative processing, the exposed silver halide crystals are developed to give a visible image and the unexposed crystals are fixed out; in reversal processing, the exposed crystals are removed with special baths, and the remaining crystals are exposed and developed instead of being fixed out. The film that is exposed in the camera is thus processed directly to a positive image. Notably, this is the procedure used to produce 35 mm color slides from reversal films such as Eastman Kodak's Ektachrome or Kodachrome.

### 5.3 Exposure and Density

Reiterating, the different objects in a scene photographed will reflect the same or different levels of radiation to the camera. If these wavelengths and levels of radiation reach the photographic material, they will cause the same or different levels of exposure, which, after processing, will be observed as the same or different densities in the developed photograph. Within the limits of the dynamic range of the photographic material, higher levels of exposure will produce higher densities (darker tones) on the negative and lower densities (lighter tones) on the positive. Brighter tones on the positive photograph thus correspond to higher exposures; allowing for differences in irradiance and atmospheric effects, higher exposures correspond to objects with higher reflectances in the wavelengths sensed.

It should be apparent that the relationships between exposure and density, and between density and development, are critical to the production and analysis of photographic images. These relationships are shown graphically, for negative or positive materials, by "characteristic curves" (Figure 5.4). These plots of density versus logarithm of exposure are also referred to as "response" curves ("film response" curves), "sensitometric" curves, or most commonly, "D-log E" curves. In essence, there is a unique D-log E curve associated with each photographic material, for each condition of development, and a family of D-log E curves associated with each type of photographic material.
Although D-log E curves are peculiar to specific photographic materials, most have a similar shape. There is a toe, a straight-line portion, and a shoulder, as shown in Figure 5.4. Exposures that fall in the straight-line portion cause linear or near-linear changes in density; exposures that fall in the toe or shoulder cause little or no change in density, with any change being non-linear.

Referring to the D-log E curves in Figure 5.4, it is seen that the photographic material can record and convey useful information over its dynamic range from the minimum density (toe) to the maximum density (shoulder). For a negative material, decreasing the exposure will produce no decrease in density below the minimum density, while increasing the exposure will produce no increase in density above the maximum density. The opposite effects occur with a positive material. The minimum density, or "gross fog," of a positive or negative film product is caused by the combined density of the unexposed emulsion (noted previously as fog density) and the film base.

The slope of the straight-line portion of a D-log E curve is referred to as the gamma (Greek letter, g) of the photographic material. In Figure 5.5, it is seen that the slope of the curve defines the change in density produced by a given change in exposure. Gamma is thus a measure of the tonal contrast of the photograph. To produce the same tonal change (i.e., change in density), photographic material with a flatter sloping D-log E curve (lower gamma, lower contrast) will need a larger change in exposure than a photographic material with a steeper sloping D-log E curve (higher gamma, higher contrast). Stated differently, a given change in exposure will produce a smaller change in density with a low gamma film than with a high gamma film.
If the straight-line portion of the D-log E curve is ill-defined, gamma may be imprecise. An alternative and more recently used measure of contrast is provided by the "contrast index," which is defined by the slope of the line between two distinct points on the D-log E curve. The lower point is located at a density 0.2 above the minimum density, and the upper point corresponds to the exposure at two log E units away from the exposure associated with the lower point.

One other parameter of interest is film "speed". By convention, faster films require less exposure to produce a given density. In Figure 5.6, for example, film A would be rated faster than film B. Film speed is determined by measuring the level of exposure at some measurable amount of density above gross fog. The familiar ASA ratings, for instance, are based on the log E value corresponding to 0.1 density above gross fog.

\[ \text{D-log E curve} \]

- film A is faster than film B
- speed is determined by measuring the exposure at some measurable amount of density above gross fog. For example, ASA ratings are based on a "speed point" = log E value corresponding to 0.1 density above gross fog.

**Figure 5.6:** Speed of a photographic film.

### 5.4 Solid State Digital Arrays

A digital frame array consists of a 2-dimensional array of photosensitive cells (pixels). The arrays may be either Charge Coupled Device (CCD) or Complimentary Metal-Oxide-Semiconductor (CMOS). Examples of both are shown in Figure 5.7. Both devices consist of rectangular arrays of individual photosites (pixels) which respond individually to incoming photons. When the camera shutter is released beginning the exposure, each pixel produces electrons in response to the incoming light and stores the electrons. Once the exposure finishes, the photosites are closed and the electrons are sampled to assess how many photons fell into each. The quantity of photons in each cavity is then sorted into various intensity levels, whose precision is determined by the radiometric resolution of the device. For most standard cameras, the levels range from 0-255, corresponding to 1 byte per band per pixel. Thus, an array with one million pixels producing a true color (RGB) image would produce 3 Mb of data representing the image.

In a CCD sensor, every pixel's charge is transferred through a very limited number of output nodes (often just one) to be converted to voltage, buffered, and sent off-chip as an analog signal. The disadvantage is in the time that it takes to off load the image data. The advantage of this design is that most of the image area is light sensitive leading to greater overall sensitivity and the response is very uniform over the array. In a CMOS sensor, each pixel has its own charge-to-voltage conversion, and the sensor often also includes amplifiers, noise-correction, and digitization circuits, so that the chip outputs digital bits. This increases the design complexity and reduces the area available for light capture. Furthermore, with each pixel performing the analog to digital conversion separately, uniformity is lower.
a) CCD image array (Kodak KAF-6303E).
   Active area: 27.65 x 18.48 mm
   Active pixels: 3072 x 2048 (6 Mpixel)
   Pixel size: 9x9 µm

   **Figure 5.7:** Two-dimensional imaging arrays.

b) CMOS image array (Samsung S5K4AW).
   Active area: ???
   Active pixels: 1280 x 960 (1.2 Mpixel)
   Pixel size: 2.8 x 2.8 µm

The gain of solid state detectors is qualitatively similar to that illustrated in Figure 5.4 for film. The solid state detector responds with voltage (or electric charge) and the results are quantized rather than continuous. Furthermore, the dynamic range of the solid state detectors is much greater with excellent linearity over the full range. This allows a solid state imaging device to collect data over a much larger range. For example, where film might be able to represent 100 distinct densities, a solid state detector are commonly designed to detect anywhere from 256 to 4096 gray values.

**Figure 5.8:** Output of a reverse-biased photodiode.

**Figure 5.9:** Response curve for a solid state detector.

\[(v_1, v_2) = \text{linearly range.}\]
\[v_{\text{min}}, v_{\text{max}} = \text{range of voltages to be digitized.}\]
\[\Delta v = \text{quantization interval}\]
\[(v_0, v_s) = \text{dark voltage and saturation voltage}\]
5.5 Spectral Sensitivity and Filters

In addition to the characteristic curves for films and radiometric response for solid state detectors, which are based on total radiation, each type of detector has an associated spectral sensitivity curve, which rates the emulsion's relative sensitivity to radiation of different wavelengths.

The most common solid state detector (and the one used in most digital cameras) is silicon, which has a sensitivity range from about 400-1000 nm. This can be extended in the UV for special applications. For observations farther into the reflective infrared, other detectors are more appropriate. These include Indium-Gallium-Arsenide (InGaAs) and Germanium (Ge) detectors. Typical response curves are illustrated in Figure 5.9

![Absolute Spectral Response](image)

Figure 5.10: Typical characterization results of a selection of photodetectors. The vertical scale is absolute responsivity in units of A/W and the horizontal scale is wavelength in nm. Other types of photodetectors are used in the UV, Far UV and the IR. (From NIST http://physics.nist.gov/Pubs/TN1421/detector.html)

With photographic films (Figure 5.10) the silver halide emulsions respond to radiation of the ultraviolet and blue regions; however sensitizing dyes are added to extend their response to green, red and near-infrared radiation. Photographic emulsions can be made sensitive to wavelength as long as about 0.9 micrometers (900 nanometers).

Although a particular emulsion will respond to radiation of a given band of wavelengths, filters may be used to restrict the radiation that reaches the emulsion (Figure 5.10). For aerial photography, filters are commonly employed to reduce atmospheric effects or to increase the spectral contrast of objects in the scene. For example, a yellow filter (e.g., Kodak's Wratten 12) is often used with panchromatic films because it absorbs radiation of ultraviolet and blue wavelengths; these shorter wavelengths are most affected by atmospheric scattering.

5.6 References


Figure 5.11: Spectral sensitivity of selected films and filters.

- **25 Red tricolor**: Used for color separation
- **58 Green tricolor**: Used for color separation
- **12 Deep Yellow**: Provides haze penetration in aerial photography.
- **47 Blue tricolor**: Used for color separation
- **89B Visually opaque**: Used for infrared photography -- especially aerial.

Visually opaque: Used for infrared photography -- especially aerial.

Infrared: Used for infrared photography -- especially aerial.