## Electromagnetic Spectrum

The **electromagnetic spectrum** is the distribution of **electromagnetic radiation** according to energy, frequency, or wavelength. The electro-magnetic radiation can be described as a stream of **photons**, which are particles traveling in a wavelike pattern, moving at the speed of light.

| Type of Radiation | Frequency Range | Wavelength Range |
|---|---|---|
| Gamma rays | $<3 \times 10^{20}$ | <1 fm |
| X rays | $3 \times 10^{17}$–$3 \times 10^{20}$ | 1 fm–1 nm |
| Ultraviolet | $7.5 \times 10^{14}$–$3 \times 10^{17}$ | 1 nm–400 nm |
| Visible | $4 \times 10^{14}$–$7.5 \times 10^{14}$ | 0.4 μm–0.75 μm |
| Near-infrared | $10^{14}$–$7.5 \times 10^{14}$ | 0.75 μm–3.0 μm |
| Midwave infrared | $5 \times 10^{13}$–$10^{14}$ | 3.0 μm–6 μm |
| Long wave infrared | $2 \times 10^{13}$–$5 \times 10^{13}$ | 6.0 μm–15 μm |
| Extreme infrared | $3 \times 10^{11}$–$2 \times 10^{13}$ | 15 μm–1 mm |
| Micro and radio waves | $<3 \times 10^{11}$ | >1 mm |

Frequencies in the visible and infrared spectral bands are measured in the millions of megahertz, commonly referred to as wavelengths rather than frequencies. Wavelength can be measured interferometrically with great accuracy and it is related to the optical frequency by the universal equation

$$c = \lambda \nu,$$

where $\lambda$ is the wavelength, $\nu$ is the optical frequency, and $c$ is the speed of light in free space ($3 \times 10^8$ m/sec).

The difference between the categories of electromagnetic radiation is the amount of energy found in their photons. The energy of a photon is inversely proportional to the wavelength, and is given by

$$\mathsf{E} = \frac{hc}{\lambda},$$

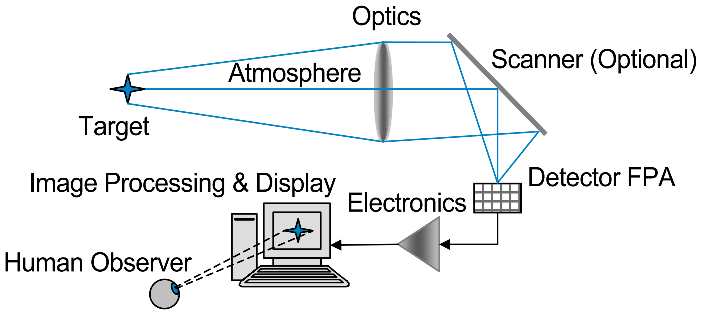
where $h$ is the Planck constant ($6.62 \times 10^{-34}$ J·sec).

Radio waves have photons with very low energies while and gamma-rays are the most energetic of all. The electromagnetic spectrum is classified based on the source, detector, and materials technologies employed in each of the spectrum regions.

## Infrared Concepts

**Infrared-imaging systems** are used to form images of targets under nighttime conditions. The target is seen because of **self-radiation** rather than the reflected radiation from the sun. Self-radiation is a physical property of all objects that are at temperatures above absolute zero (i.e., 0 K = −273.15°C).

In order to make this radiation visible, the infrared system depends on the interaction of several subsystems.



The self-radiation signature is determined by the **temperature** and the surface characteristics of the target. Gases in the atmosphere limit the frequencies that this radiation can be transmitted. The configuration of the optical system defines the **field-of-view (FOV)**, the **flux collection efficiency**, and the **image quality**. These parameters, along with the detector interface, impact the radiometric accuracy and **resolution** of the resulting image. The detector is a transducer that converts the optical energy into an electrical signal, and electronics amplify this signal to useful levels.

For typical terrestrial and airborne targets **Planck's equation** dictates that, within the range of temperatures of 300 K to 1000 K, emission of radiation occurs primarily in the infrared spectrum. However, the background is self-luminous as well, causing terrestrial targets to compete with background clusters of similar temperature. Infrared images have much lower **contrast** than corresponding visual images, which have orders of magnitude higher reflectance and emittance differences.

## Infrared Detectors

Infrared detectors are transducers that sample the incident radiation and produce an electrical signal proportional to the total flux incident on the detector surface. There are two main classes of infrared detectors: **thermal** and **photon detectors**. Both types respond to absorbed photons, but they use different response mechanisms. Differences in these mechanisms lead to variations in speed and spectral responsivity, and sensitivity. Thermal detectors depend on the changes in the resistance, capacitance, voltage, or mechanical displacement of the sensing materials that result from temperature changes caused by the heating effect of the incident radiation. The change in these electrical properties with input flux level is measured by an external electrical circuit. The thermal effects do not depend on the photonic nature of the incident infrared radiation; they have no inherent long-wavelength cutoff. Their sensitivity limitation is due to thermal flux and/or the spectral properties of the protective window in front of them. The response rate of a thermal detector is slow because of the time required for the device to heat up after the energy has been absorbed. Examples of different classes of thermal detectors are: **bolometer**, **pyroelectric**, **thermopile**, **Golay cells**, and **superconductors**.

The two basic types of semiconductor-photon detectors are photoconductors and photovoltaics, or photodiodes. The photonic effects in these devices result from direct conversion of incident photons into conducting electrons within the material. An energetic photon excites an electron from the nonconducting state into a conducting state instantaneously, causing a change in the electrical properties of the semiconductor material that can be measured by an external circuit. Photon detectors are very fast and their response speed is generally limited by the RC product of the readout circuit.

Detector performance is described in terms of **responsivity**, **noise-equivalent power**, or **detectivity**.

## Primary Sources of Detector Noise

Noise is a random fluctuation in electrical output from a detector, and must be minimized to increase the performance sensitivity of an infrared system. Sources of optical-detector noise are classified as either external, such as photon flux and preamplifier noise, or internal noise, which includes shot, generation-recombination, one over frequency ($1/f$), and temperature fluctuation, and are a function of the detector area, bandwidth, and temperature.

It is possible to determine the limits of detector performance set by the statistical nature of the radiation to which it responds. Such limits set the lower level of sensitivity, and can be ascertained by the fluctuations in the signal or background radiation falling on the detector.

Random noise is expressed in terms of an electrical variable such as a voltage, current, or power. If the voltage is designated as a random-noise waveform $v_n(t)$ and a certain probability-density function is assigned to it, its statistics as a function of three statistical descriptors are found.

**Mean**: $\overline{v_n} = \dfrac{1}{T}\displaystyle\int_0^T v_n(t)dt \quad \text{[volts]},$

**Variance or mean-square**:

$$\overline{v_n^2} = \overline{(v_n(t) - \overline{v_n})^2} = \frac{1}{T}\int_0^T [v_n(t) - \overline{v_n}]^2 dt \quad [\text{volts}^2],$$

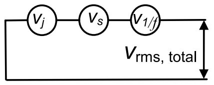
**Standard deviation**:

$$v_{\text{rms}} = \overline{\Delta v_n} = \sqrt{\frac{1}{T}\int_0^T [v_n(t) - \overline{v_n}]^2 dt} \quad \text{[volts]},$$

where $T$ is the time interval, and the standard deviation is the rms noise of the random variable.

Linear addition of independent intrinsic noise sources is carried out in power (variances) not in voltage noise (standard deviation); the total rms noise of random quantities are added in quadrature:

$$\Delta v_{\text{rms,total}} = \sqrt{\Delta v_{\text{rms},1} + \Delta v_{\text{rms},2} + \cdots + \Delta v_{\text{rms},n}}.$$



Assuming three sources of noise are present; Johnson, shot, and $1/f$ noise:

$$V_{\text{rms,total}}^2 = V_j^2 + V_s^2 + V_{1/f}^2$$

## Noise Power Spectral Density

Noise can also be described in the frequency domain. The **power spectral density (PSD)**, or the mean-square fluctuation per unity frequency range, provides a measurement of frequency distribution of the mean-square value of the data (i.e., distribution of power).

For random processes, frequency can be introduced through the autocorrelation function. The time average **autocorrelation** function of a voltage waveform may be defined as

$$c_n(\tau) = \lim_{T\to\infty} \frac{1}{T}\int_{-T/2}^{T/2} v_n(t)v_n(t+\tau)\,dt,$$

where the autocorrelation is the measure of how fast the waveform changes in time. The PSD of a wide-sense stationary random process is defined as the Fourier transform of the autocorrelation function (Wiener-Kinchine theorem)

$$\mathrm{PSD} = N(f) = \mathsf{F}\{c_n(\tau)\} = \int_{-\infty}^{\infty} c_n(\tau)e^{-j2\pi f\tau}d\tau.$$

The inverse relation is

$$c_n(\tau) = \mathsf{F}^{-1}\{N(f)\} = \int_{-\infty}^{\infty} N(f)e^{j2\pi f\tau}df.$$

Using the central ordinate theorem yields

$$c_n(0) = \int_{-\infty}^{\infty} N(f)df = \int_{-\infty}^{\infty} v_n^2(t)dt = \overline{v_n^2(t)}.$$

The average power of the random voltage waveform is obtained by integrating the PSD over its entire range of definition.

Uncorrelated noise such as white noise implies that its autocorrelation function is a delta function. The PSD of such random processes is a constant over the entire frequency range, but in practice, the PSD is constant over a wide but final range (i.e., band-pass limited).