Sensitivities in Photometric Units

The most commonly available CCD sensors are the RS170 type, the performance of which has traditionally been specified using photometric units. To assist in making comparisons and choosing replacement systems from DALSA we will show how the relevant units can be converted. For example, the sensitivity specifications are often expressed in lux, measured with a given lens f-number and source color temperature. The use of Automatic Gain Control (AGC) in the RS170 camera electronics to boost the output of the camera in low light levels reduces the S/N ratio and can, in some cases degrade the minimum responsivity of the system. Therefore it is important to understand the conditions under which the specifications are valid. Measurements of the minimum sensitivity are often defined where S/N = 1.

Given the color temperature of the light source its spectral luminance can be calculated using Planck's Law. This data can then be converted to radiometric units by multiplying by the photometric curve (see CCD technology primer). So, assuming T = 3200K the spectral illuminance will have a peak at 906nm (see example 5 in the Practical Radiometry Application Note). To convert from a photometric unit to a radiometric unit at a specific wavelength simply multiply the data by the photometric curve. Conversely, to convert from a radiometric unit to a photometric unit at a specific wavelength you divide the data by the photometric curve. When the whole spectrum is known, as it is here, the process must be carried out for all wavelengths. However, when the sensitivity of the camera is measured using a broad spectrum light source such as a halogen lamp, the spectral curve of the sensor will automatically be folded into the data. Without knowledge of the spectral response curve of the light source it is not possible to recover the camera response in radiometric units for a particular frequency. The light incident on the lens will be focused onto the sensor, and therefore the irradiance of the sensor will depend on the magnification and the iris setting. In some cases an IR cutoff filter is specified, which further complicates the conversion to radiometric data. Hence, DALSA specifications use radiometric units with details of the sensor spectral responsivity to enable complete and accurate calculations to be made for all scenarios as necessary.

Sensitivity of DALSA Sensors in Photometric Units

The first step in calculating the photometric sensitivity of a sensor is to define the light source. In this case it will be a tungsten halogen lamp with a color temperature of 3200K. Assuming it to be a perfect Black Body the spectral radiance, $L_{e\lambda}$, is given by Planck's Law

$$L_{e\lambda} = \frac{1.19 \times 10^{23}}{\lambda^5 \left[exp\left({}^{14388000}/_{\lambda T} \right) - 1 \right]}$$

where λ is given in nm, T in Kelvin and $L_{e\lambda}$ in W m^{-2} nm^{-1} sr^{-1}. The resulting curve is shown in Figure 2. In many applications, it is often appropriate to use an infrared filter, and the resulting curve will be similar to that shown in Figure 3. With knowledge of the spectral radiance it is possible to calculate the spectral irradiance at the sensor for a given lens system. To preserve generality it will be assumed that the lens, iris and object-lens separation are such that the spectral irradiance, $E_{e\lambda}$, is given by $E_{e\lambda} = L_{e\lambda} / f_g$, where f_g is a constant that depends only on the chosen lens and the geometry (f_g is expressed below). Given the radiometric spectral responsivity of the sensor, $R_e(\lambda)$ in V/(J/m^2), it is possible to calculate the output from the sensor using

$$V_o = {}^{Z_r \Delta t}/_{f_g} \qquad where \qquad Z_r = \int L_{e\lambda} R_e(\lambda) d\lambda$$

$$\Delta t = integration\ time$$

Given that the minimum noise level at the output from the sensor is N_o, then it is possible to equate this to the sensor output so that $N_o = V_o = Z_r \ \Delta t / f_g$. Hence, we can recover an expression for f_g, a measure of how much the light reaching the sensor has to be reduced using the lens stop to reach the noise level: $f_g = Z_r \ \Delta t / N_o$.

The photometric response of the sensor can be found from the radiometric response using the CIE luminous efficiency curve $V(\lambda)$, which describes the human eye response. This conversion is defined by

$$E_v = {}^{Z_v 683}/_{f_g} \qquad where \qquad Z_v = \int L_{e\lambda} V(\lambda) d\lambda$$

Hence the noise equivalent illuminance, NEE_v, is given by

$$NEE_v = \frac{N_o 683}{\Delta t}\left(\frac{Z_v}{Z_r}\right) \qquad lux.$$

The value of N_o is determined by the sensor, and is typically 50µV without reset noise and about 120µV with reset noise. The integration time varies with application, but for an RS170 camera it is designed to be 1/30 s, or 1/60 s per field in interlace mode depending on the technique employed. Hence, the noise equivalent illuminance is determined by the ratio Z_v / Z_r, which depends on the spectral response of the sensor and the color temperature of the light source. It is possible to define a photometric sensitivity, Rv using

$$R_v = \frac{1}{683}\left(\frac{Z_v}{Z_r}\right)^{-1} \qquad V \quad lux^{-1}s^{-1}$$

Table 1 provides photometric responsivities for selected sensors from each of DALSA's product families (Line Scan, TDI Line Scan, and Area Scan).

Table 1. Photometric Responsivities

Source Color temp. (Kelvin)	IA-D1 (V/lx-s)	IL-P1 (V/lx-s)	IL-E2 (V/lx-s)
2400	19.70	15.95	812
3200	10.24	8.90	430
3800	7.76	7.06	330
4800	5.92	5.73	258
5600	5.22	5.27	232
6000	4.99	5.13	223
6500	4.78	5.00	216
9600	4.21	4.79	200
12000	4.08	4.82	199

Figure 1. CIE Luminous Efficiency Curve

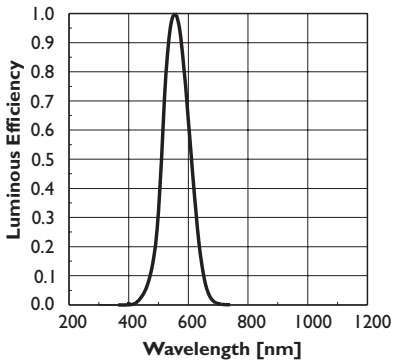

Figure 2. Example Black Body Curve

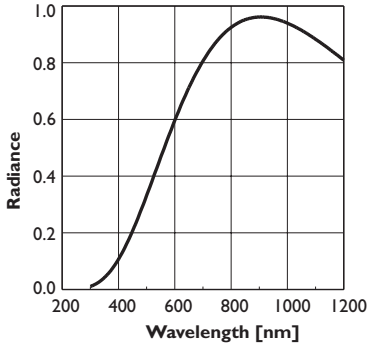

Figure 3. Black Body with IR Filter