Predicting the performance of a photodetector

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Comments and corrections and questions are welcome.

The performance of a photodetector system can be predicted from the parameters D* (detectivity), Responsivity, time constant and saturation level, and from some knowledge about the noise in the system. No photodetector should be purchased until a prediction has been made.

- **Detectivity and NEP**

The principal issue usually facing the system designer is whether the system will have sufficient sensitivity to detect the optical signal which is of interest. Detector manufacturers assist in making this determination by publishing the figure of merit "*D**". *D** is defined as follows:

$$D^* \equiv \frac{\sqrt{A \times \Delta f}}{NEP} \qquad \text{(equation 1)}$$

where *A* is the detector area in cm^2
Δf is the signal bandwidth in hertz
and *NEP* is an acronym for "Noise Equivalent Power", the optical input power to the detector that produces a signal-to-noise ratio of unity (S/N=1).

*D** is a "figure of merit" and is invaluable in comparing one device with another. The fact that S/N varies in proportion to $\sqrt{A}$ and $\sqrt{\Delta f}$ is a fundamental property of infrared photodetectors.

- **Active Area**

Consider a target about which we wish to measure some optical property. If the image of the target is larger than the photodetector, some energy from the target falls outside the area of the detector and is lost. By increasing the detector size we can intercept more energy. Assuming the energy density at the focal plane is constant in watts/cm^2, doubling the linear dimension of the detector means that the energy intercepted increases by $2^2 = 4$ times. But *NEP* increases only as $\sqrt{4} = 2$. Conversely, if the image of the target is small compared to the detector size, and if there are no pointing issues related to making the image of the target fall on the photodetector, then halving the linear dimension of the photodetector will similarly double S/N, since the input optical signal S stays constant while the NEP DECREASES by a factor of $\sqrt{4} = 2$. The moral of this story is: Neither throw away photons nor detector area. Know your system well enough to decide on an optimized active area.

- **Bandwidth**

Error theory tells us that signal increases in a linear fashion but noise (if it is random) adds 'RMS'. That is, Signal increases in proportion to the time we observe the phenomenon, but Noise according to the square root of the observation time. This means that if we observe for a microsecond and achieve signal-to-noise of β, in an integration time of 100 microseconds we can expect S/N of $\sqrt{100}\beta = 10\beta$. Bandwidth is related to integration time by the formula

$$\Delta f = \frac{1}{2\pi\tau} \qquad \text{(equation 2)}$$

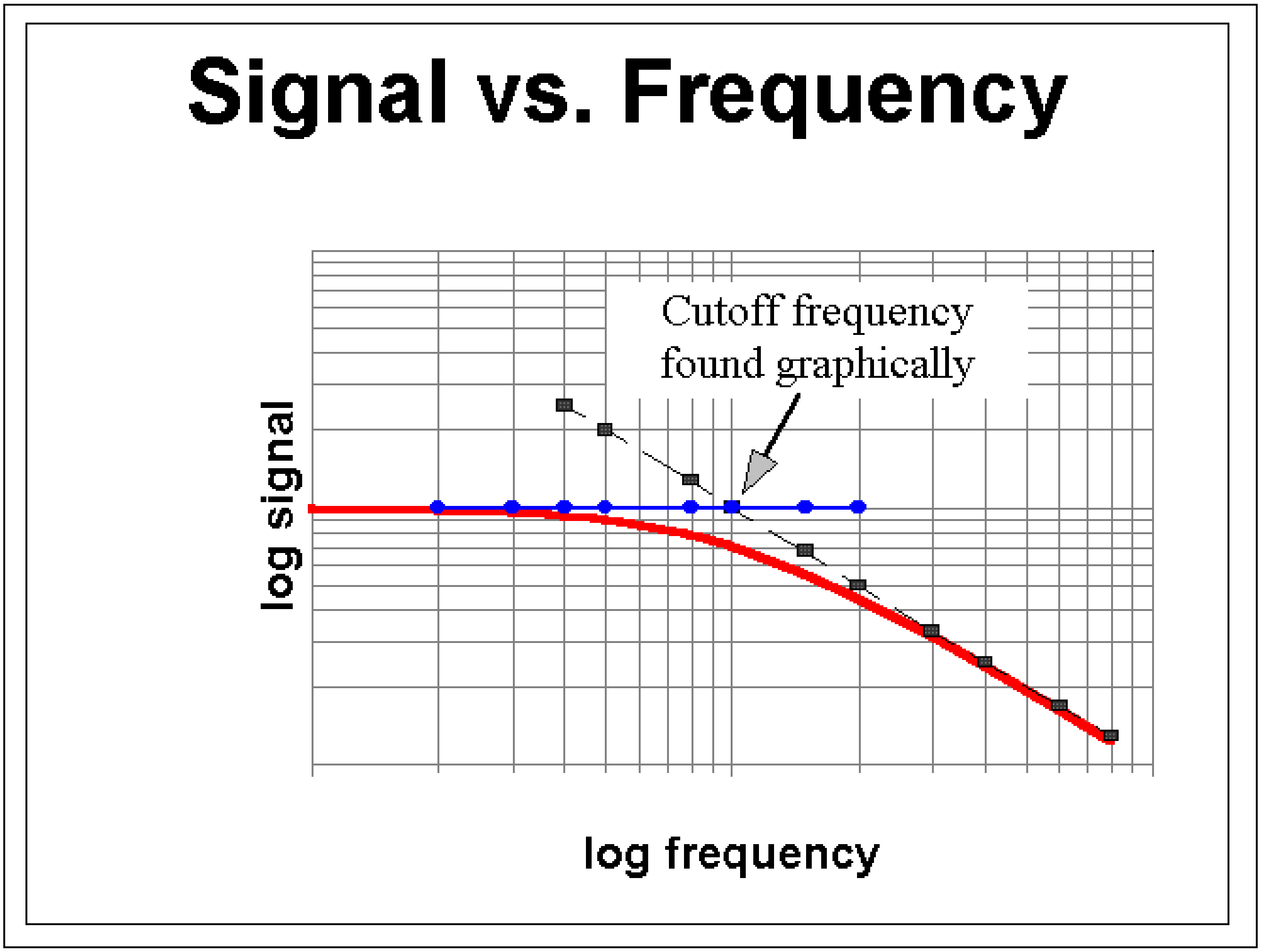
where τ is the integration time or "time constant" of the system in seconds. Time constant τ is the time it takes for the detector (or the system) output to reach a value of $\left(1-\frac{1}{e}\right) \cong 63\%$ of its final, steady state value.

- **Signal**

Signal in all quantum photodetectors is constant versus frequency at low frequencies but begins to decline as the frequency increases. The decline is a function of the time constant. If S_{low} is the signal at f_{low}, a few hertz, the signal at arbitrary frequency f » f_{low} is

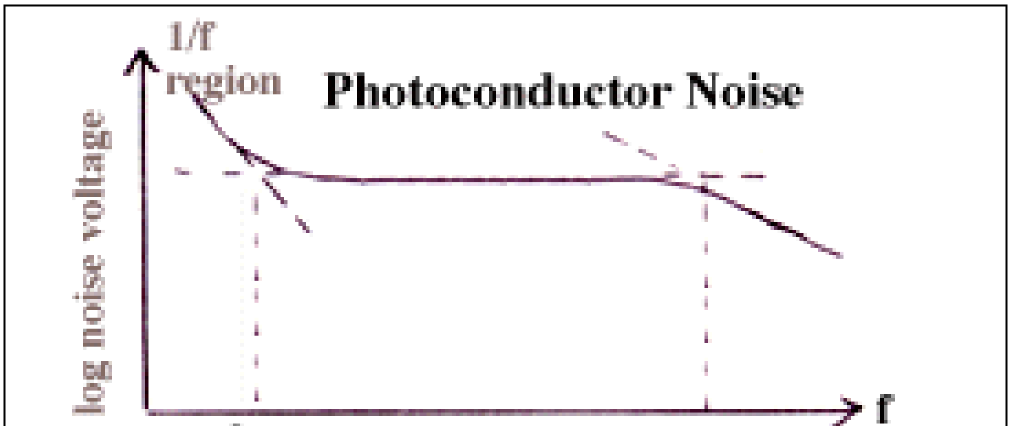
$$S_f = \frac{S_{low}}{\sqrt{1+(2\pi\tau)^2}} \qquad \text{(equation 3)}$$

This is graphically illustrated below. Frequency f_c is the point at which $S_f = \frac{1}{\sqrt{2}} S_{low}$.



- **Noise**

Noise is not as simple as signal. Photoconductive devices like PbS, PbSe, and most HgCdTe exhibit "flicker" or 1/f noise, which is excess noise at low frequencies. Consequently, Signal-to-Noise ratio and *D** are degraded at these frequencies. 1/f noise actually varies as $\sqrt{\frac{1}{f}}$ in voltage terms. At high frequencies, the detector noise actually decreases according to the same relationship as signal decreases. However, the difficulty in constructing following amplifier electronics that are significantly lower in noise than the photodetector results in system always having a noise at high frequencies that is no better than noise at low frequencies. The following set of graphs illustrates this.

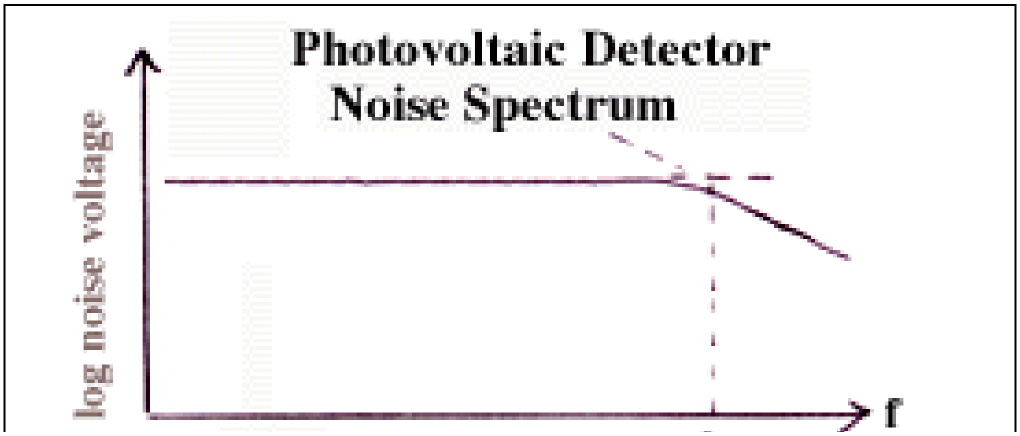


To predict low frequency performance of a photoconductor, the extent to which *D** is degraded by 1/f noise must be estimated. Either of the following ways is applicable:

1. use the manufacturer's published graphical data of *D** versus frequency to determine the multiplication factor N_{excess} to use to convert minimum guaranteed *D** at its measured frequency to *D** at the frequency of interest.
2. use the 1/f "corner frequency" $f_{corner} > f_{low}$ reported by the manufacturer to estimate the degradation factor at f_{low} as

excess noise factor $N_{excess} = \sqrt{\frac{f_{corner}}{f_{low}}}$ (equation 4)

In contrast to photoconductors, photovoltaic detectors normally have no 1/f noise. Signal is flat to or near DC and therefore *D** is constant below the high frequency roll-off region, so no low frequency correction need be made.



- **Spectral response correction**

The *D** of a quantum detector varies with wavelength λ. The detector manufacturer typically guarantees *D** at the wavelength of peak response, *D*(peak)*. When using the device at another wavelength λ, the *D** should be corrected by an appropriate factor:

$$R_\lambda = \frac{(response - at - \lambda)}{(response - at - peak)}$$

$$D^*_\lambda = D^*_{peak} \times R_\lambda \qquad \text{(equation 5)}$$

where the relative response at wavelength λ is estimated by inspection of spectral response curves or other data supplied by the manufacturer.

Therefore, the optical input power required to produce a signal-to-noise ration of 1:1 for a stated system response time and wavelength becomes:

Case 1: Photoconductor at low frequency:

$$NEP_\lambda = \frac{\sqrt{A \times \Delta f}}{D^*_\lambda} \times N_{excess} \qquad \text{(equation 6)}$$

Case 2: Photovoltaic detector at low to moderate frequency:

$$NEP_\lambda = \frac{\sqrt{A \times \Delta f}}{D^*_\lambda}$$ (equation 7)

Case 3: Photoconductor or photovoltaic frequency at higher frequency:

$$NEP_\lambda = \frac{\sqrt{A \times \Delta f}}{S_f \times D^*_\lambda}$$ (equation 8)

This yields an estimate of the input optical power to achieve a voltage output with S/N=1.

- **Upper Limits**

Another important question is the dynamic range of the system, e.g. the ratio of the maximum signal available to the *NEP* of the system. The upper limit of the system is typically set by the electrical gain of the preamp or the vertical gain of the oscilloscope used to display the signal, combined with the maximum output signal of the preamp or the maximum vertical deflection of the oscilloscope. The dynamic range of the system is then expressed in multiples of the system *NEP*.

Let the preamp gain be *G*. Let the responsivity of the detector in volts per watt (or volts per division in the case of an oscilloscope) at low frequency be R_{low} and at frequency f let it be R_f where

$$R_f = R_{low} \times S_f$$ (equation 10)

The voltage signal from the detector into the preamp or oscilloscope when S/N=1 corresponding to this responsivity will be

$$V_f = NEP \times R_f$$ (equation 11)

Then the output of the preamp at frequency f and S/N=1 will be

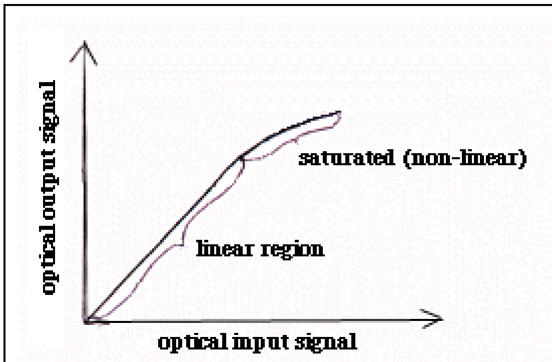
$$V_{preamp} = V_f \times G$$ (equation 12)

Let the maximum output of the system be Ψ_{preamp} volts (or $\Psi_{vertical}$ vertical divisions in the case of an oscilloscope). The multiple of the NEP that corresponds to the maximum output Ψ_{preamp} will therefore be

Preamp Dynamic Range $$D = \frac{\Psi_{preamp}}{V_f \times G}$$ (equation 13)

Of course, with an oscilloscope it is usually possible to turn down the gain and thus increase the dynamic range. However, preamps usually have fixed gain. In that case the input optical must be attenuated in order to keep the output from the preamp from saturating.

Sometimes the photodetector itself will saturate before the preamp. Some process, thermal or photonic, intrinsic to the photodetector may limit it's output. In this case, the maximum available (saturation) output signal should be specified by the device manufacturer, typically as a not-to-exceed output voltage $\Psi_{detector}$.. Graphically the situation is illuatrated as follows:



Case 1: Dynamic Range limited by the preamp

$$D = \frac{\Psi_{preamp}}{V_f \times G} < \frac{\Psi_{\det ector}}{V_f}$$ (equation 14)

Case 2: Dynamic Range limited by the detector

$$D = \frac{\Psi_{\det ector}}{V_f} < \frac{\Psi_{preamp}}{V_f \times G}$$ (equation 15)

This completes our prediction of system performance. We have calculated the input optical signal that corresponds to S/N=1, and the maximum output that can be extracted from the system in terms of a multiplier of the minimum input signal. The multiplier is “dynamic range”.

- **System options**

As the designer, you have the following additional degrees of freedom in designing a system:

1. You may increase the size of his optics in order to deliver more optical energy to the photodetector. The key concept to remember is that throughput in any optical system, defined as $T = A \times \Omega$, where A is area in cm^2 and Ω is solid angle field of view in steradians, is a constant in the system. If A_D is detector area and Ω_D is detector FOV, then collector area A_C and collector FOV Ω_C are at best satisfy $A_C \times \Omega_C = T = A_D \times \Omega_D$. Increasing the collector aperture decreases the FOV.

2. You may increase the efficiency of his optics (transmittance and reflectance optimization, etc).

3. You may increase the power of his source in a cooperative, active system (though not in a passive one).

4. You may increase the time he observes the signal, that is decrease the bandwidth and increase the time constant.

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- **Appendix: Sample Calculations**

See next page.

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PVM-10.6	Responsivity 200 mV/W	D*(10.6 um) 1.5E+07 cm.Hz$^{1/2}$/watt

Assume detector saturation for CW signal is	*20*	*mV*
Assume detector saturation for single fast pulse is	*600*	*mv*
Assume wavelength is 10.6 microns		
Assume active area is 1x1 mm		
Assume resistance is 50 ohms		

	volts
Amplifier 481-1X to 481-20X saturates at………	**5**
481-200X saturates at …..	**1**
493A and 493A/40 saturates at	**5**

System Elements	Time Constant (nsec)	3dB Frequency (MHz)	Gain (voltage)	System Responsivity (V/W)	Optical signal for S/N=1 (NEP, microwatts)	Electrical signal for S/N=1 (millivolts)	*CW case* S/N at Detector Saturation	*Pulsed case* S/N at Detector Saturation	S/N at Preamp Saturation
PVM-10.6 unamplified	<1	160	1	0.2	84	0.02	1186	35576	no preamp
PVM-10.6 with 493A/40	<1	500	100	20	149	2.98	671	20125	1677
PVM-10.6 with 493A	<1	500	10	2	149	0.30	671	20125	16771
PVM-10.6 with 481-200	<1	200	40	8	94	0.75	1061	31820	1326
PVM-10.6 with 481-100	1.5	100	80	16	67	1.07	1500	45000	938
PVM-10.6 with 481-50	3	50	200	40	47	1.89	2121	63640	2652
PVM-10.6 with 481-20	8	20	200	40	30	1.19	3354	100623	4193
PVM-10.6 with 481-10	15	10	400	80	21	1.69	4743	142302	2965
PVM-10.6 with 481-5	30	5	960	192	15	2.86	6708	201246	1747
PVM-10.6 with 481-1	150	1	4000	800	6.7	5.33	15000	450000	938
PVM-10.6 with 481-0.1	1500	0.1	4000	800	2.1	1.69	47434	1423025	2965
PVM-10.6 with 481-0.01	15000	0.01	4000	800	0.7	0.53	150000	4500000	9375
	Time constant τ and 3dB frequency are related by $f=1/(2\pi\tau)$ - slower of detector or preamp shown	BW of preamp indicated	from product lit and typical 50 Ω detector resistance	detector responsivity times gain	Square root of the detector area times square root of the 3dB frequency divided by the D* from product lit	Optical signal at S/N=1 times System Responsivity	Saturation level for CW signal divided by Optical signal at S/N=1	Saturation level for Pulsed signal divided by Optical signal at S/N=1	Clipping level for preamp divided by electrical signal for S/N=1

Shading indicates saturation of detector or preamp for CW case

This rather complicated chart is intended to illustrate how the performance of our detectors (in this example the model PVM-10.6 with 1x1 mm active area and typical values of responsivity and D*) is affected by variously by (a) saturation of the detector itself or (b) by saturation of a following preamp. The shaded cells indicate the lower of S/N for CW signals and indicates whether it is the detector that saturates first or the preamp that saturates first. We loosely define saturation in the detector as the point at which output deviates from linearity by 20%; in the preamp we define saturation as the output at which the signal is clipped. Notice that detector saturation is MUCH LOWER for the CW case. The most common signal is quasi-CW (for example an RF-modulated CO2 laser) and should be considered CW. Any pulsed laser with a duty cycle over 1% or pulse length longer than 10 microseconds is probably more like CW than pulsed.