

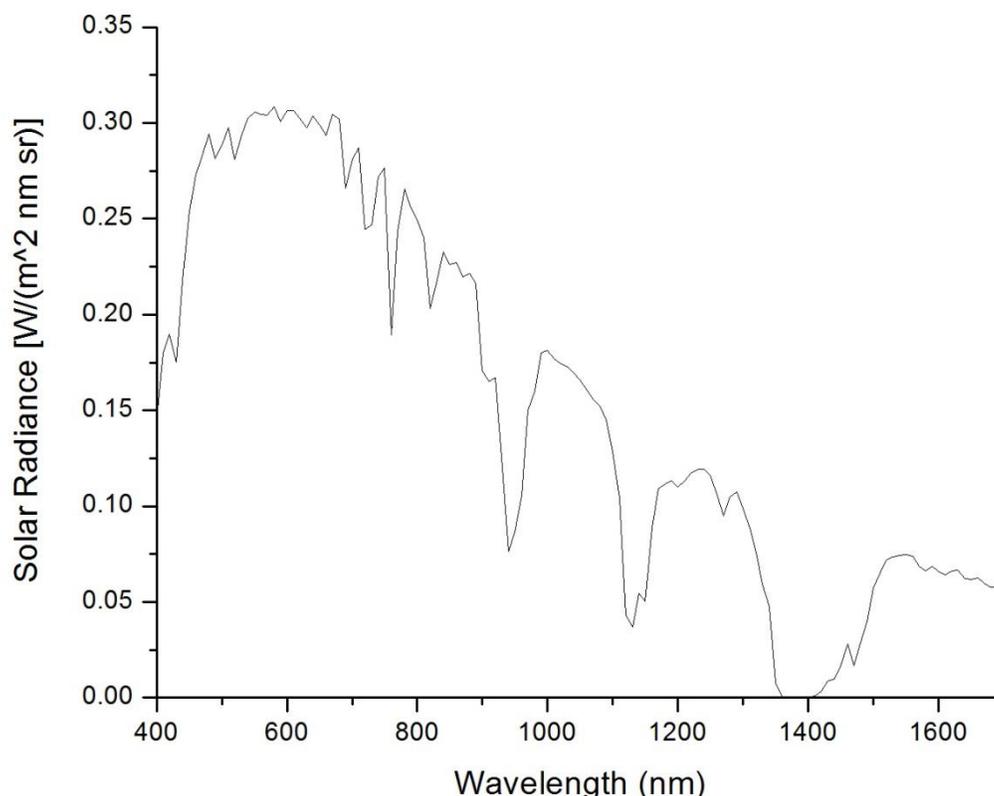
## Signal-to-Noise Ratio (SNR) discussion

The signal-to-noise ratio (SNR) is a commonly requested parameter for hyperspectral imagers. This note is written to provide a description of the factors that affect the SNR. We begin by examining the signal collected by a hyperspectral imager,  $\Phi(\lambda)$ , in units of Joules, collected by each detector element (spatial, spectral channel), which is calculated to a good approximation using the formula:

$$\Phi(\lambda) = \frac{\pi L(\lambda) A_D \varepsilon(\lambda) (\Delta\lambda) (\Delta t)}{4(f/\#)^2 + 1}$$

It is worthwhile discussing each factor in this equation to understand how to best optimize the SNR.

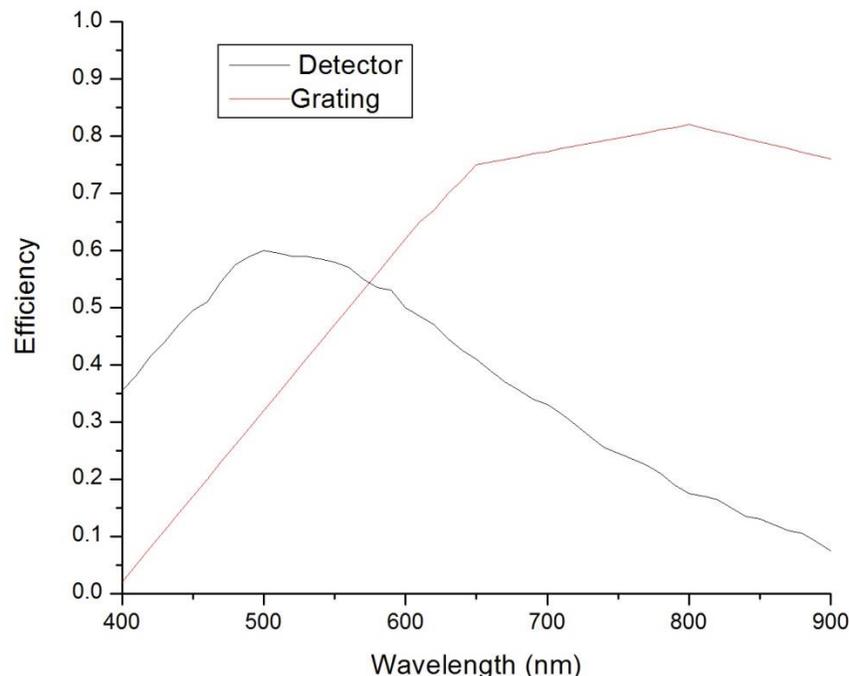
$L(\lambda)$  is the at-sensor spectral radiance at wavelength  $\lambda$  in units of  $W/(m^2 \text{ sr nm})$ . In layman's terms, this tells you the brightness of the light coming into the imager. If you have very bright light, your signal will increase as you would expect. Thus, in general, you can increase your Signal (and thus your SNR) with brighter illumination. Generally, the illumination changes with wavelength. For example the solar spectrum in typical atmospheric conditions is shown below. Note that illumination becomes weaker at both short ( $\sim 400$  nm) and long wavelengths, and thus the signal (and SNR) degrade at short and long wavelengths. The visible wavelength range is 400-700 nm.



### Solar Radiance in typical atmospheric conditions.

$A_D$  is the detector area in  $m^2$ . In layman's terms, this is the area of each pixel on the camera. Large pixel-area increases your signal, and pixel-binning effectively increases the pixel-area. Because it is very complicated and expensive to integrate new cameras, this is usually not a parameter you can adjust.

$\epsilon(\lambda)$  is the optical system efficiency which includes optical throughput of the lenses, the diffraction grating efficiency, and the detector quantum efficiency. The Grating and Detector efficiencies both change significantly with wavelength and as a result the SNR of an imaging spectrometer is wavelength dependent.



**Diffraction Grating and Detector efficiency as a function of wavelength for the Pika II.**

$\Delta\lambda$  is the optical bandwidth spread out across the detector area (pixel).

$\Delta t$  is the integration time (shutter) in seconds. This is one of the easiest parameters to adjust. The MAXIMUM integration time is  $1/(\text{frame rate})$  for the Pika II. Thus, to increase your signal (and SNR), do the following: (1) Decrease your frame rate; and (2) then increase your shutter.

$(f/\#)$  is the imaging lens f-number, which is a measure of the instrument's aperture. For maximum signal (and best SNR), one should set the  $f/\#$  on the objective lens to the  $f/\#$  of the instrument. (Alternatively, A higher  $f/\#$  setting on your objective lens will provide a deeper depth of field.) The smallest acceptable  $f/\#$ s for the Pika imaging spectrometers are:

Pika Model	f/#
Pika II	3
Pika XC	2.4
Pika NIR	1.8

### Signal-to-Noise Ratio (SNR)

Once the Signal is known, the signal-to-noise ratio as a function of wavelength,  $SNR(\lambda)$ , is calculate using the following equation:

$$SNR(\lambda) = \frac{\Phi(\lambda) \frac{\lambda}{hc}}{\sqrt{\left[\Phi(\lambda) \frac{\lambda}{hc}\right] + [B(i_{Dark})\Delta t] + [B(e_{Read}^2)]}}$$

where  $h$  is Plank's constant,  $c$  is the speed of light,  $B$  is the number of binning operations performed to collect the signal,  $i_{Dark}$  is the dark current in electrons/sec, and  $e_{Read}$  is the read noise in electrons. The nomenclature for the terms is as follows. The Numerator is the Signal in units of electrons. The Denominator is the Noise in units of electrons, whose terms, going from left to right, are shot noise, dark noise, and read noise. Shot noise is due to noise in the signal itself and cannot be avoided. For the short integration times of most applications with Pika imaging spectrometers, dark noise is insignificant. Read noise is dependent on temperature, the camera, and other factors, and is typically around 10 for visible/near-infrared cameras.

The maximum possible SNR is dependent on the well depth for the spectral channel, the dark noise, and the read noise. These maximum possible SNR values are listed below.

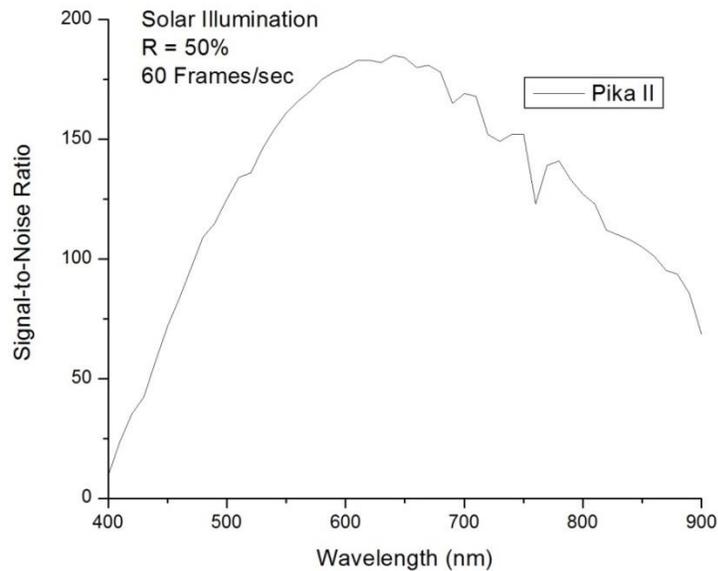
Imager	Maximum SNR
Pika II	198
Pika XC (Allied Camera)	315
Pika NIR	1,935

\*Pixels are binned along the spectral axis to match the instrument spectral resolution.

When you combine all the factors in the equation above, one can generate a plot of the Signal-to-Noise Ratio (SNR) as a function of wavelength. However, because it is dependent on ALL the factors listed above, one must be careful to note how the results change in differing conditions. For example, halogen lighting will produce a different SNR than solar lighting; high frame rates will lead to lower SNRs than slow frame rates, and so forth.

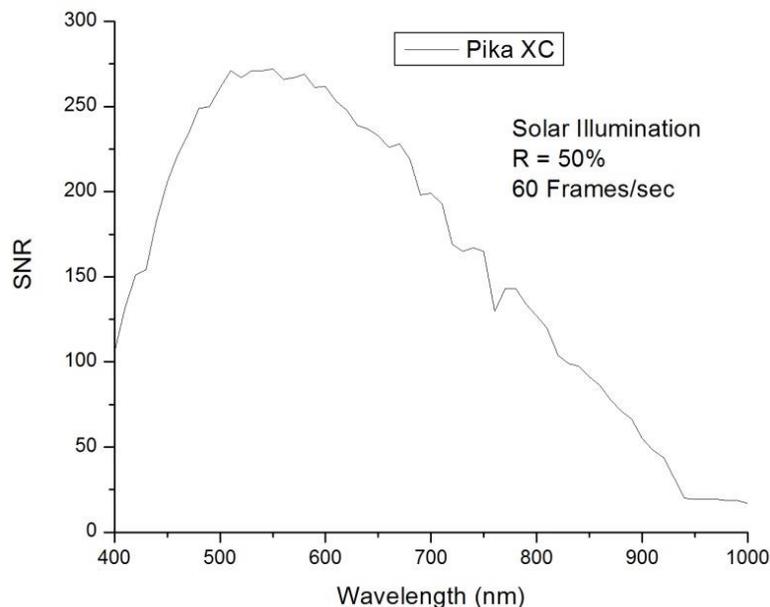
A typical SNR plots are shown below for an object in solar illumination with a reflectance of 50%. The other parameters for each imager are listed.

**Pika II:** Bandwidth ( $\Delta\lambda$ ) = 2.1 nm;  $f/\#$  =3; Integration time ( $\Delta t$ ) = 0.0167 sec



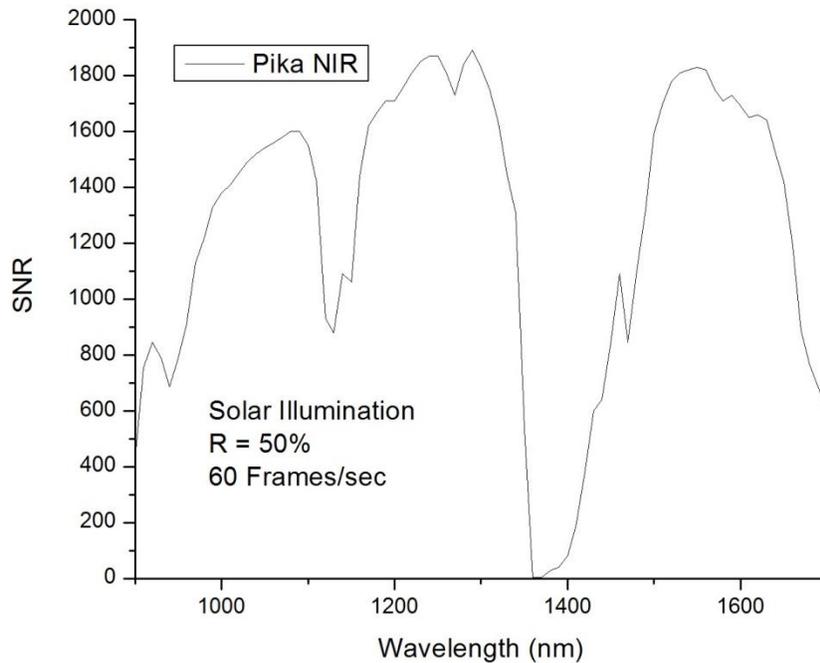
**Pika II SNR as a function of wavelength with typical solar illumination viewing an object with 50% reflectance at 60 frames/second.**

**Pika XC:** Bandwidth ( $\Delta\lambda$ ) = 2.4 nm;  $f/\#$  =2.4; Integration time ( $\Delta t$ ) = 0.0167 sec



**Pika XC SNR as a function of wavelength with typical solar illumination viewing an object with 50% reflectance at 60 frames/second.**

**Pika NIR: Bandwidth ( $\Delta\lambda$ ) = 5.4 nm; f/# =1.8; Integration time ( $\Delta t$ ) = 0.0167 sec**



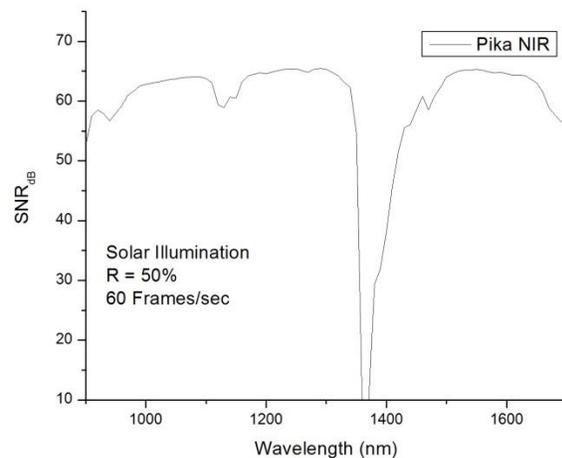
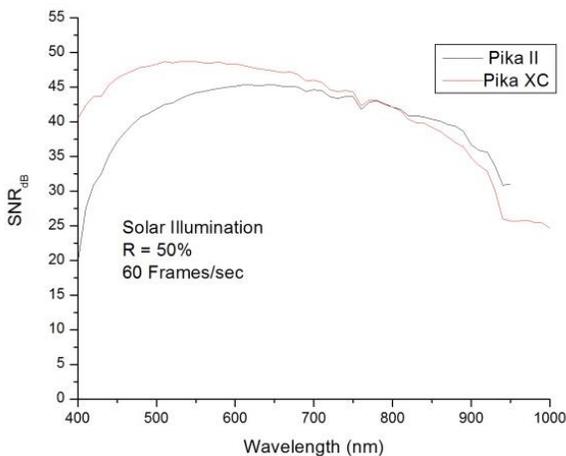
**Pika NIR SNR as a function of wavelength with typical solar illumination viewing an object with 50% reflectance at 60 frames/second.**

Note: The prominent dips in these SNR plots are due to features in the solar spectrum.

Optical SNR are often provided in units of decibels (dB), which is given as:

$$SNR_{dB} = 20 \log(SNR(\lambda))$$

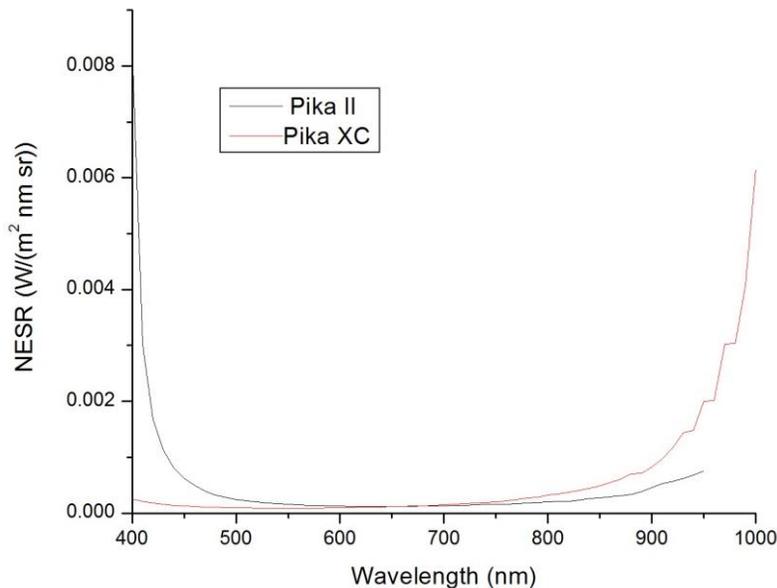
SNR<sub>dB</sub> plots for the Pika II, Pika XC, and Pika NIR for the same conditions in the SNR plots above are provided below.



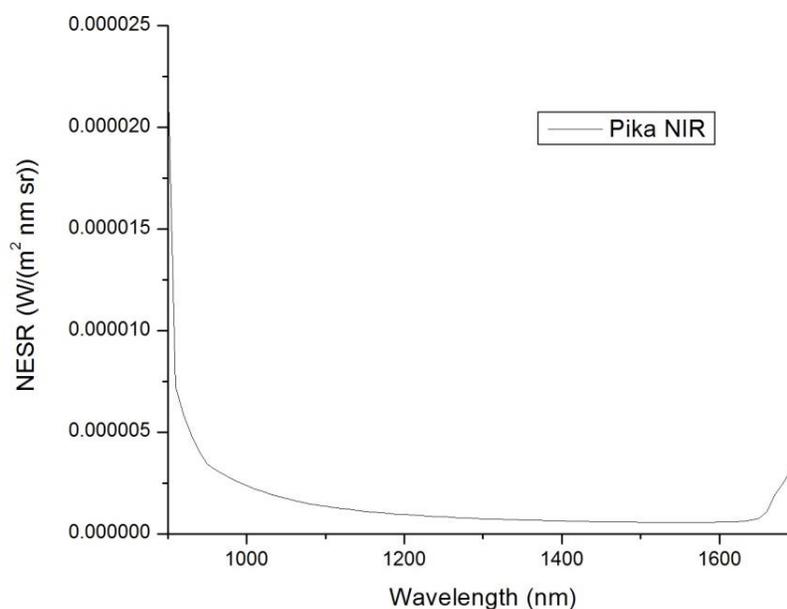
**SNR<sub>dB</sub> as a function of wavelength for the same parameters as above.**

## Noise Equivalent Spectral Radiance (NESR)

Another noise metric is the Noise Equivalent Spectral Radiance (NESR). This is the spectral radiance required to obtain a SNR of 1. As one would expect, this is dependent on the internal optical efficiency of the instrument – it will be large for spectral channels where efficiency is relatively poor and small where efficiency is good.



### Pika II & Pika XC NESR as a function of wavelength.



### Pika NIR NESR as a function of wavelength.