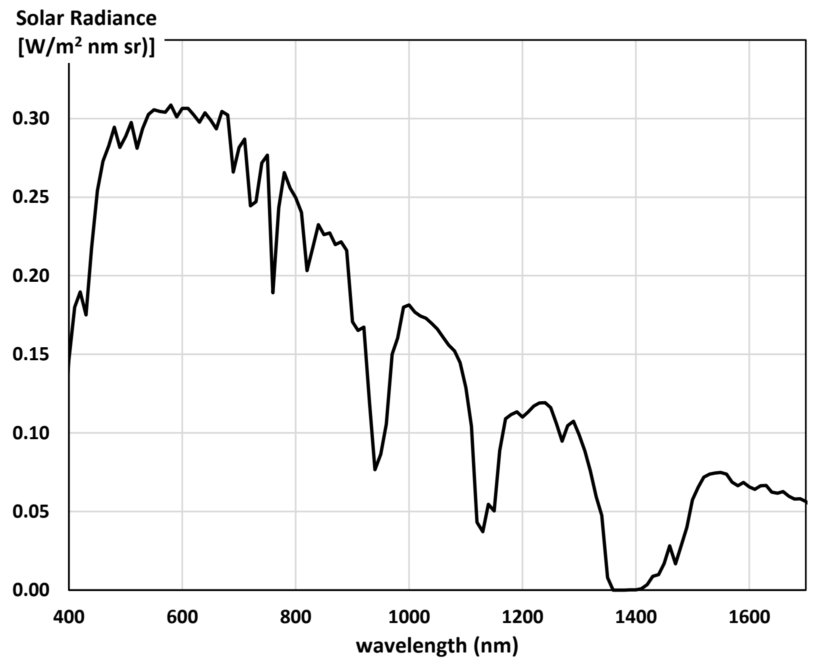
Signal-to-Noise Ratio (SNR) discussion

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 SNR. We begin by examining the signal collected by a hyperspectral imager, $\Phi(\lambda)$, in units of Joules, collected by each detector element (which is a unique spatial and spectral channel), and is calculated to a good approximation using the formula:

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

Each factor in this equation is discussed below:

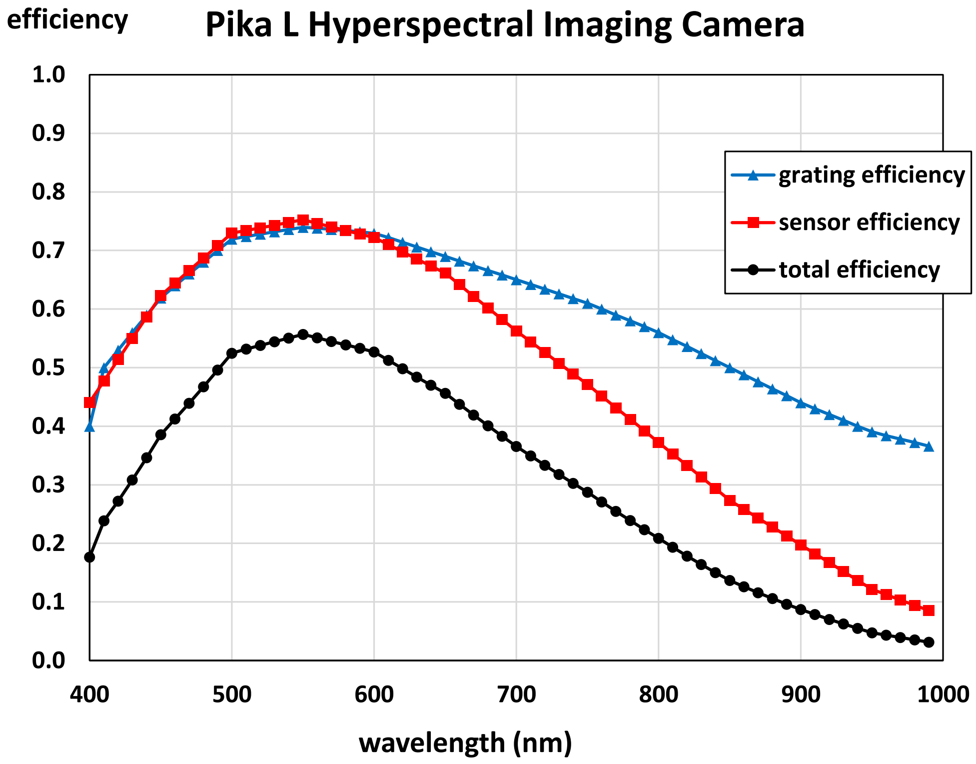
L(λ) is the at-sensor spectral radiance at wavelength λ in units of W/(m^2·sr·nm). In layman's terms, this tells you the brightness of the light coming into the imager. If you have very bright light, your signal will increase as you would expect. Thus, in general, you can increase your signal (and thus 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 (~400 nm) and long wavelengths, and thus the signal (and SNR) degrade at short and long wavelengths.



Solar Radiance in typical atmospheric conditions.

A_D is the detector area in m^2. This is the area of each pixel on the camera. Large pixel-area increases your signal. 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 that can be adjusted.

$\varepsilon(\lambda)$ 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 strongly wavelength dependent.



Grating, sensor, and total efficiencies of the Pika L hyperspectral camera as a function of wavelength.

$\Delta\lambda$ is the optical bandwidth in nm spread out across each pixel.

Δt is the integration time (also known as the “shutter time” and “exposure time”) in seconds. This is one of the easiest parameters to adjust. The MAXIMUM integration time is 1/(frame rate). Thus, to increase the signal (and SNR), do the following: (1) Decrease the frame rate; and (2) then increase the integration time.

(f/#) is the imaging lens f-number, which is a measure of the instrument’s aperture. For maximum signal (and best SNR), the f/# on the objective lens should be set to the f/# of the instrument. There is no benefit to setting the f/# lower than instrument's value. A higher *f/#* setting on the 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 *(discontinued Jan 2016)*	3.0
Pika L	2.4
Pika XC2	2.4
Pika NIR	1.8

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 per second, and e_{Read} is the read noise in electrons.

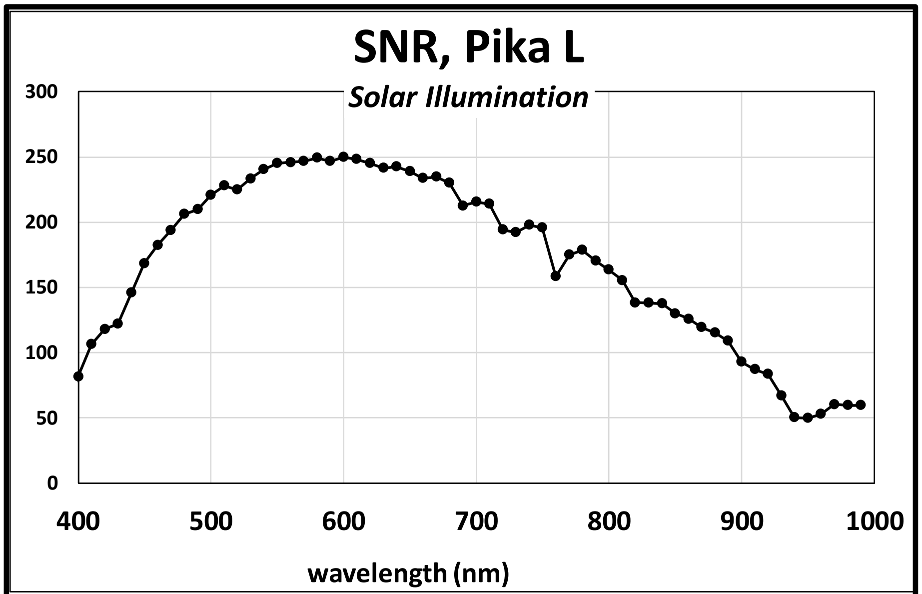
The nomenclature for the terms is as follows: the numerator is the signal in units of electrons. The denominator is the noise in units of electrons, whose terms, going from left to right, are shot noise, dark noise, and read noise. Shot noise is noise in the signal itself and cannot be avoided. For the short integration times of most applications with Pika imaging spectrometers, dark noise is insignificant. Read noise is dependent on temperature, the sensor, and other factors, but for Resonon's hyperspectral cameras it is fairly small, typically less than 20 electrons.

The maximum possible SNR is dependent on the sensor's well depth, dark noise, read noise, and binning. These maximum possible SNR values are listed in the table below.

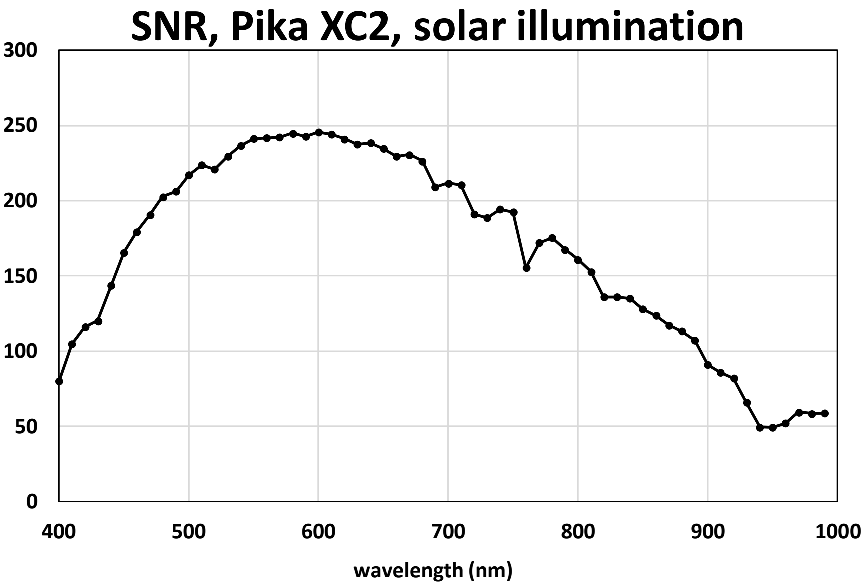
Pika Model	**Maximum SNR**
Pika II *(discontinued Jan 2016)*	198
Pika L	347
Pika XC2	361
Pika NIR	1936

When you combine all the factors above, one can generate a plot of the Signal-to-Noise Ratio (SNR). 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.

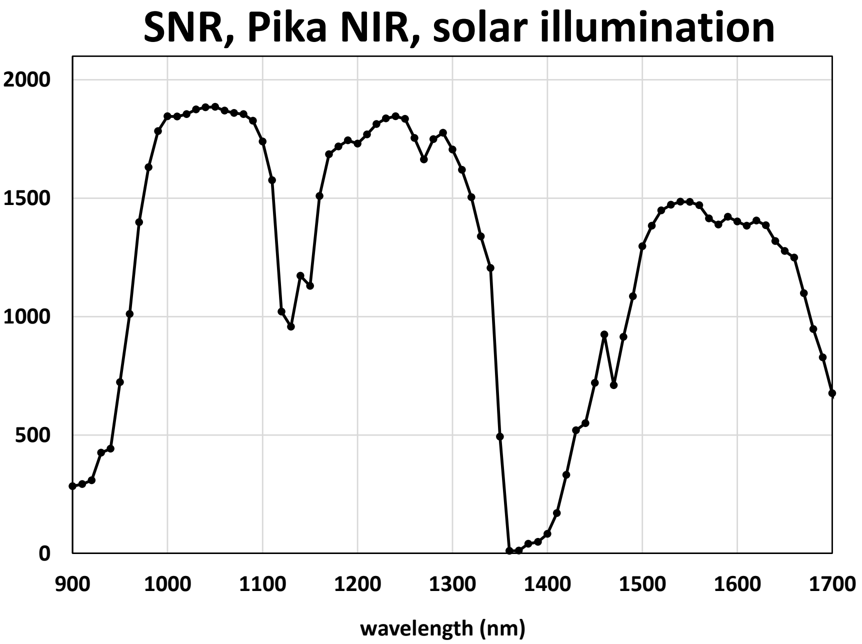
Below are shown typical SNR plots for Resonon's hyperspectral cameras in solar illumination and with an integration time such that the brightest channel has a 95% fill factor.



Pika L SNR as a function of wavelength with typical solar illumination.



Pika XC2 SNR as a function of wavelength
with typical solar illumination.



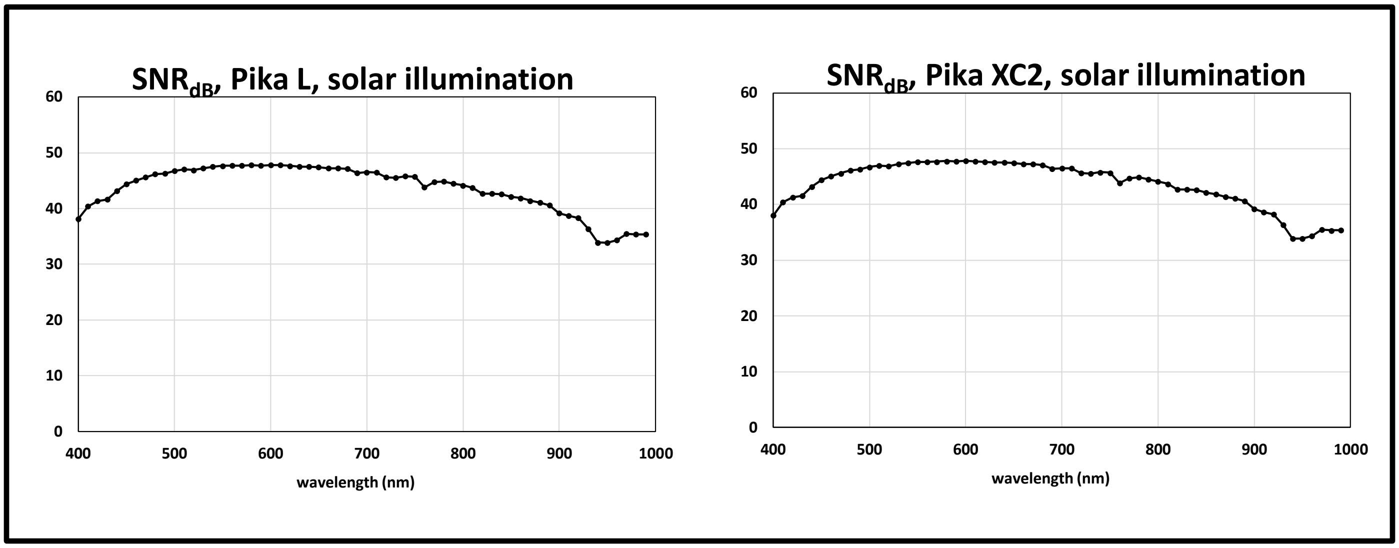
Pika NIR SNR as a function of wavelength
with typical solar illumination.

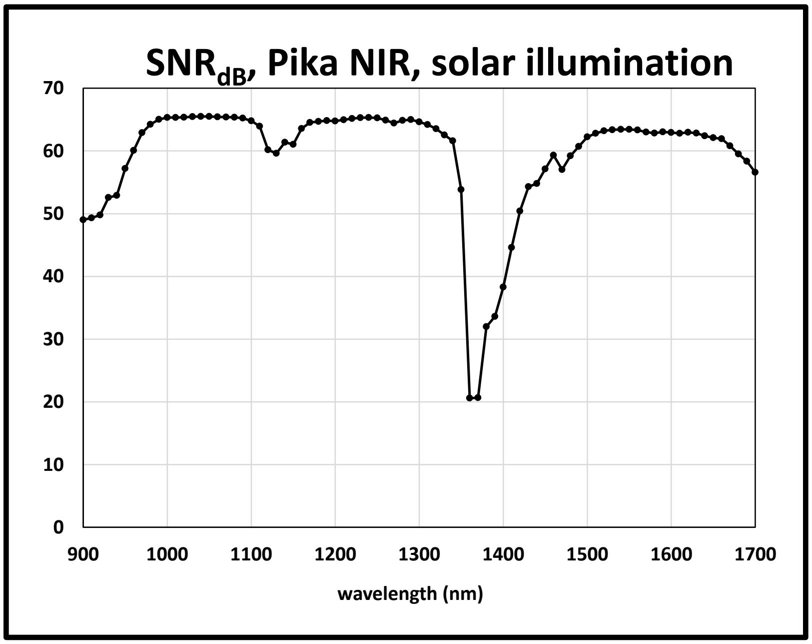
Note that the prominent dips in the SNR plots are due to features in the solar spectrum.

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

$$SNR_{dB} = 20\ log_{10}(SNR(\lambda))$$

SNR$_{dB}$ plots for the Pika L, Pika XC2, and Pika NIR for the same conditions in the SNR





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.

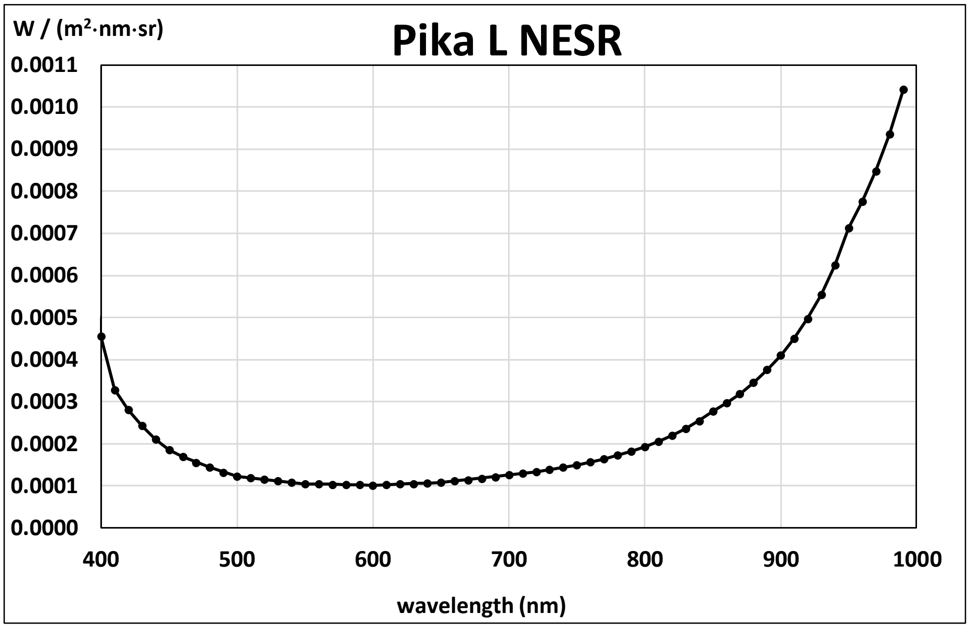
The NESR can be found by setting the equation for SNR equal to 1 and then solving for $L(\lambda)$:

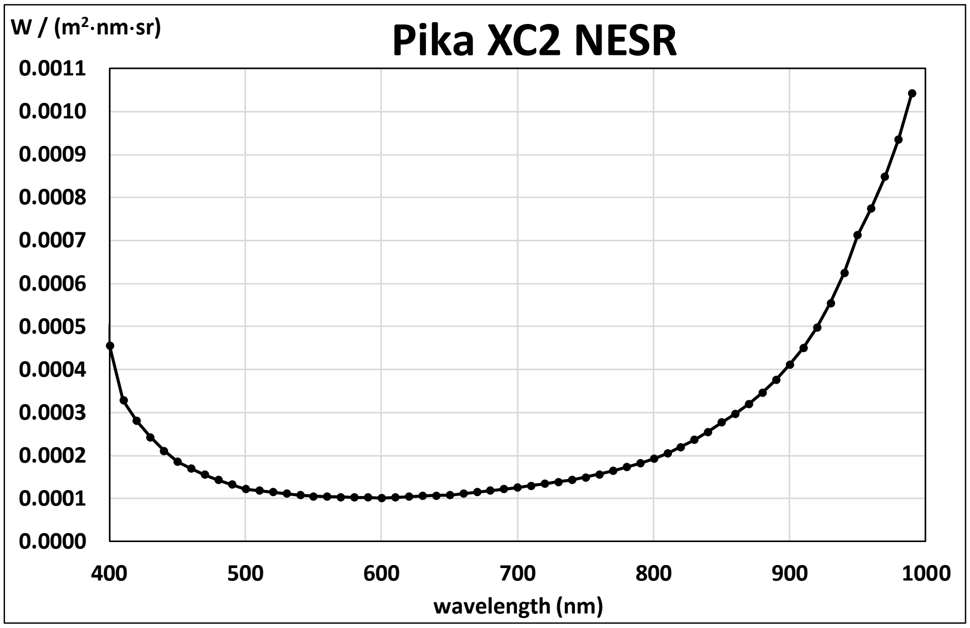
$$NESR(\lambda) = \frac{1 + \sqrt{1 + 4(Bi_{dark}(\Delta t) + Be_{read})}}{2Q(\lambda)}$$

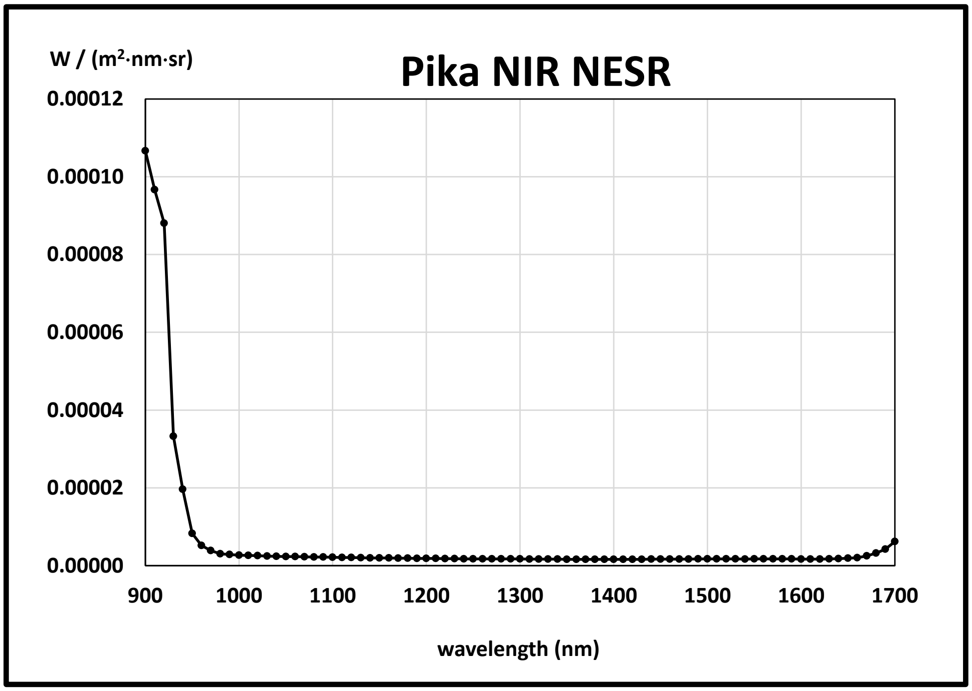
where

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

Graphs showing the NESR of Resonon's hyperspectral imagers are below.




W / (m²·nm·sr)
Pika XC2 NESR
0.0011
0.0010
0.0009
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0.0000
400
500
600
700
800
900
1000
wavelength (nm)


W / (m²·nm·sr)
Pika NIR NESR
0.00012
0.00010
0.00008
0.00006
0.00004
0.00002
0.00000
900
1000
1100
1200
1300
1400
1500
1600
1700
wavelength (nm)