Optical Bench Design

Avaspec-ULS Optical Bench Design: Symmetrical Czerny-Turner

1. Detector
2. SMA Connector
3. Grating
4. Slit, mode stripper
5. 2nd mode stripper
6. Collimating mirror
7. Focusing mirror
8. CPC light traps
9. CPC light traps
10. DCL-UV/VIS
11. OSC-filter

The heart of most AvaSpec fiber-optic spectrometers is an optical bench with 37.5, 50, 75 or 100 mm focal length, developed in a symmetrical Czerny-Turner design. Light enters the optical bench through a standard SMA-905 connector and is collimated by a spherical mirror. A plain grating diffracts the collimated light; a second spherical mirror focuses the resulting diffracted light. An image of the spectrum is projected onto a 1-dimensional linear detector array.

Avantes AvaSpec-HS2048XL high-sensitivity spectrometers have a revolutionary optical bench design with multiple toroid mirrors which ensure that the full numerical aperture of the fiber entrance will be projected on the backthinned CCD array.

All of our optical benches have a number of components installed inside, allowing a wide variety of different configurations, depending on the intended application. The choice of these components such as the diffraction grating, entrance slit, order-sorting filter, and detector have a strong influence on system specifications such as sensitivity, resolution, bandwidth and stray-light. Each of these specification will be discussed in detail in the following paragraphs.

How to configure a spectrometer for your application

The modular AvaSpec line of instruments provides you with a number of configuration options to optimize the optical and spectroscopic performance of your instrument for your application.

This section provides you some guidance on how to choose the right grating, slit, detector and other configuration options, to be installed in your AvaSpec.

Wavelength Range

In the determination of the optimal configuration of a spectrometer system the wavelength range is key parameter that defines the appropriate grating choice.
If you are looking for a wide (broadband) wavelength range, we recommend the use of a 300 lines/mm grating. For lesser range (approximately 500 nm) but higher resolution, you might consider a 600 lines/mm. Higher lines/mm gratings (1200, 1800, 2400, 3600) provide higher resolution for applications that require this (see Grating selection table in the spectrometer product section). Broadband gratings provide the greatest flexibility but may not provide the best performance for specific applications. Contact an Avantes Sales Engineer or representative for a recommended grating configuration.

Detector Choice

The choice of your wavelength range along with the demands of your measurement speed and accuracy often suggests the appropriate detector for your application.

Avantes offers a variety of different detector types, each with different sensitivity curves (see Figure 3a and 3b on page 20).
The AvaSpec instrument line is divided into multiple groups based on general requirements. The AvaSpec-Starline is comprised of general purpose UV/VIS instruments with low-cost CCD or CMOS detectors. The AvaSpec Sensline is comprised of higher performance back-thinned CCDs and thermo-electrically cooled CCD UV/VIS instruments. These instruments are particularly better in the UV and NIR range, compared to standard CCD and CMOS detectors. The AvaSpec NIRLine is comprised of instruments with InGaAs arrays for longer wavelength measurements, ranging from 900-2500 nm. For applications where the size of the instrument is a critical factor, Avantes offers the CompactLine with spectrometers that have a small form factor.

For high-speed applications, the 2048 pixel CMOS detectors in the AvaSpec-ULS2048CL from the StarLine are normally the best options. For low-light level applications such as fluorescence and Raman, the SensLine instruments may be the most appropriate. The AvaSpec NIRLine features 6 different InGaAs detectors for various applications.

The modularity and inter-compatibility of the AvaSpec line also make it possible to combine two or more detectors in a single instrument enclosure to provide optimal performance over a broad wavelength range. For example, an AvaSpec StarLine (UV/VIS) spectrometer can be combined with a NIRLine spectrometer to enable measurements from 200-2500 nm in a single instrument.

Optical Resolution & Slit size

If high optical resolution is required, you may want to consider a grating with higher lines/mm (1200, 1800, 2400, 3600), thus limiting the range of the instrument to a more narrow range. Additionally, it is advisable to consider a detector with 2048 or 4096 pixels and a small slit (10 or 5 µm). For the best resolution with all other criteria of lesser importance, the AvaSpec-4096CL with a 5 micron slit is optimal.

Slit size is a key factor in determining both resolution and throughput of the optical bench. It is important to balance your need for resolution with the need for sensitivity and throughput of the optical bench. If resolution is optimized without considering the need for throughput, you may not have adequate light to get a stable measurement. As previously mentioned, for optimal resolution our smallest slit (5 microns) is recommended. If your application does not require the highest possible resolution and is not one that has an excess of light (laser measurement for example), we recommend that you consider as larger slit to maximize throughput into the optical bench.
The AvaSpec-RS with replaceable slit makes your spectrometer a versatile instrument for both high-resolution and high-sensitivity measurements.

Sensitivity

When considering sensitivity, it is very important to distinguish between photometric sensitivity (How much light do I need for a detectable signal?) and chemometric sensitivity (What absorbance difference level can still be detected?)

a. Photometric Sensitivity

For the best photometric sensitivity a combination of a high-throughput optical bench and a high quantum-efficiency (QE) detector is recommended. The instruments in the AvaSpec SensLine are specifically optimized for photometric sensitivity.

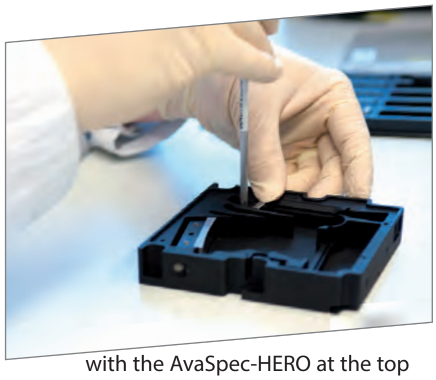
For example fluorescence applications require high photometric sensitivity. Avantes AvaSpec-HS2048XL is the highest performance instrument we offer for this application. For Raman applications, where the combination of resolution and sensitivity is required, we commonly recommend our AvaSpec-HERO with TEC cooling. To further enhance photometric sensitivity, we recommend the use of a detector collection lens (DCL-UV/VIS or DCL-UV/VIS-200), which is a cylindrical lens with focuses light from larger core fiber-optics and bundles down onto the smaller detector pixels.
For additional photometric sensitivity, a larger slit and a 300 line/mm grating to minimize light dispersion are available. Some more demanding applications also require thermo-electric cooling of the CCD detector (see product section AvaSpec-ULS2048LTEC and AvaSpec-HERO) to minimize noise and increase dynamic range at long integration times (up to 60 seconds).

For our detector types the photometric sensitivity is given in Table 4 (page 19) and Table 5 (page 21), the spectral sensitivity for each detector is depicted in Figures 3a and 3b.

b. Chemometric Sensitivity

To detect drastical different absorbance values, close to each other with maximum sensitivity, you need high Signal to Noise (S/N) performance. The detectors with best S/N performance are again in

the AvaSpec SensLine series spectrometers



with the AvaSpec-HERO at the top of the line. The S/N performance can also be enhanced by averaging multiple spectra. The square root of the number of averages translates to the improvement in signal to noise.

Timing and Speed

The data capture process is inherently faster with linear detector arrays and no moving parts as compared with a monochromator design, however, there are optimal detectors for each application. For high-speed applications such as measurements involving pulsed lasers and light sources, we recommend the AvaSpec-ULS2048CL-EVO spectrometers.
These instruments support high-speed data acquisition with the capability of starting an acquisition as fast as within 1.3 microseconds of receiving an external trigger. Since data transfer time is critical for these applications, Avantes' unique Store-to-RAM mode enables on board storage of up to 5000 spectra to the instrument RAM buffer.

The above parameters are the most important in choosing the right spectrometer configuration. Please contact our application engineers to optimize and fine-tune the system to your needs. Table 1 on the next page provides a quick reference guide for spectrometer selection for many common applications. The system recommendations in this table are for simple configurations of mostly single channel spectrometers.
For more elaborate explanations of specific explanations, see the applications section at the back of the catalog.

Table 1 Quick Reference Guide for Spectrometer Configuration

Application	AvaSpec-type	Grating	WL range (nm)	Coating	Slit (µm)	FWHM Resolution (nm)	DCL	OSF	OSC
Biomedical	ULS2048CL	NB	500-1000	-	50	1.2	-	475	-
Chemometry	ULS2048CL	UA	200-1100	-	50	2.3	-	-	OSC-UA
Color	ULS2048CL	BB	360-780	-	200	4.5	X/-	-	-
Fluorescence	ULS2048x64TEC ULS2048XL	VA, VB, UB	350-1100, 300-800	-	200	9.2 4.6	X	305	OSC
	HS2048XL	HS-500-0.33	200-1160	-	200	10.0	-	-	OSC
Fruit-sugar	ULS2048CL	IA	800-1100	-	50	6.4	X	600	-
Gemology	ULS2048	VA	350-1100	-	25	1.2	X	-	OSC
High-resolution	ULS2048CL	VD	600-700	-	10	0.12	-	550	-
	ULS4096CL	VD	600-700	-	10	0.05	-	550	-
High UV/NIR-Sensitivity	HS2048XL	HS-500-0.33	200-1160	-	200	10.0	-	-	OSC
Irradiance	ULS2048CL	UA	200-1100	DUV	50	2.3	X/-	-	OSC-UA
Laserdiode	ULS4096CL	NC	700-800	-	10	0.18	-	600	-
LED	ULS2048CL	VA	350-1100	-	25	1.2	X/-	-	OSC
LIBS	ULS4096CL	D,E,F	200-900	DUV	10	0.09	-	-	-
Raman	ULS2048LTEC ULS2048x64TEC	NC	780-930	-	25	0.3	X	600	-
Solar	ULS2048XL	VA	300-1100		50	2.5		305	OSC
Thin Films	ULS2048CL	UA	200-1100	DUV	100	4.6	X	-	OSC-UA
UV/VIS/NIR	ULS2048CL	UA	200-1100	DUV	25	1.2	X/-	-	OSC-UA
	ULS2048XL	UA	200-1100	-	25	1.5	-	-	OSC-UA
NIR	NIR512-1.7TEC	NIR200-1.5	1000-1750	-	25	6.0	-	1000	-
	NIR256-2.5TEC	NIR100-2.5	1000-2500	-	50	15.0	-	1000	OSC-NIR

The grating can only be changed by Avantes.
Therefore, choose your grating wisely.
Our application specialists are available to support you with your choice.
In general, a higher resolution means a lower bandwidth.
By combining multiple spectrometers
in our AvaSpec-Dual or rack-mountable versions,
you can create one virtual spectrometer with high-resolution
and high bandwidth.

How to choose the right grating

A diffraction grating is an optical element that separates incident polychromatic radiation into its constituent wavelengths. A grating consists of series of equally spaced parallel grooves formed in a reflective coating deposited on a suitable substrate. The way in which the grooves are formed separates gratings in two types, holo-graphic and ruled.

The ruled gratings are physically formed onto a reflective surface with a diamond on a ruling machine. Gratings produced from laser constructed interference patterns and a photolithographic process are known as holographic gratings.

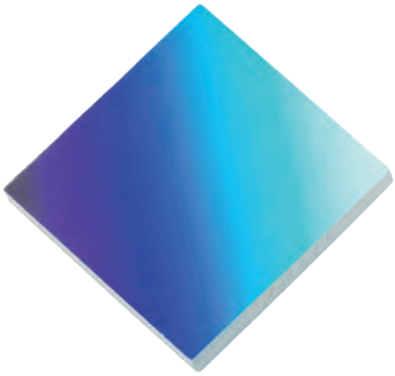
Avantes AvaSpec spectrometers come with a permanently installed grating that must be specified by the user. Additionally, the user needs to indicate what wavelength range needs to reach the detector. Sometimes the specified usable range of a grating is larger than the range that can be projected on the detector. In order to cover a broader range, a dual or multi-channel spectrometer can be chosen. In this configuration each channel may have different gratings covering a segment of the range of interest.

In addition to broader range, a dual or multi-channel spectrometer also affords higher resolution for each channel.
For each spectrometer type a grating selection table is shown in the spectrometer platform section.

Table 2 illustrates how to read the grating selection table. The spectral range to select in Table 2 depends on the starting wavelength of the grating and the number of lines/mm; the higher the wavelength, the bigger the dispersion and the smaller the range to select.

In Figure 2, grating efficiency curves are shown. When looking at the grating efficiency curves, please realize that the total system efficiency will be a combination of fiber transmission, grating and mirror efficiency, detector quantum efficiency and coating sensitivities. The dual-blazed grating is a 300 lines/mm broadband grating (covering 200-1100 nm) that has optimized efficiency in both UV and NIR.

Different diffraction gratings



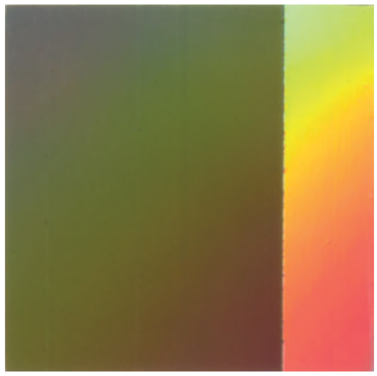


Table 2 Example of Spectral Range and Gratings

Use	Useable range (nm)	Spectral range (nm)	Lines/mm	Blaze (nm)	Order code
UV/VIS/NIR	200-1100	900	300	300	UA
UV/VIS	200-850	520	600	300	UB
UV	200-750	250-220*	1200	250	UC
UV	200-650	165-145*	1800	UV	UD
UV	200-580	115-70*	2400	UV	UE
UV	220-400	70-45*	3600	UV	UF
UV/VIS	250-850	520	600	400	BB
		800			VA

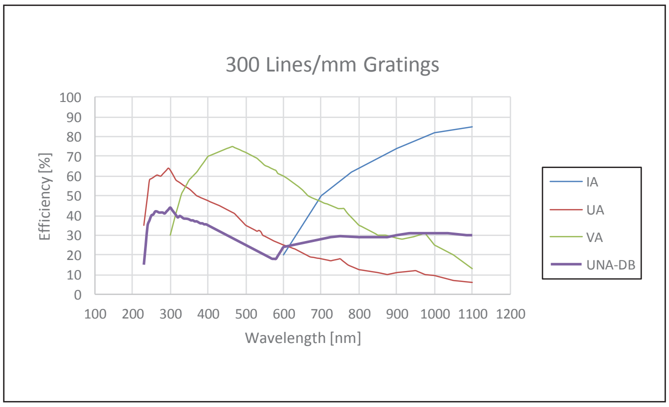
Please select Spectral range bandwidth from the useable Wavelength range, for example: grating UE (200-315 nm)
* the spectral range depends on the starting wavelength of the grating; the higher the wavelength, the smaller the range. For example: Grating UE (510-580 nm)

The order code is defined by 2 letters: the first is the Blaze (U= 250/300 nm or UV for holographic, B=400 nm, V=500 nm or VIS for holographic, N=750 nm, I=1000 nm) and the second the nr of lines/mm (Z=150, A=300, B=600, C=1200, D=1800, E=2400, F=3600 lines/mm)

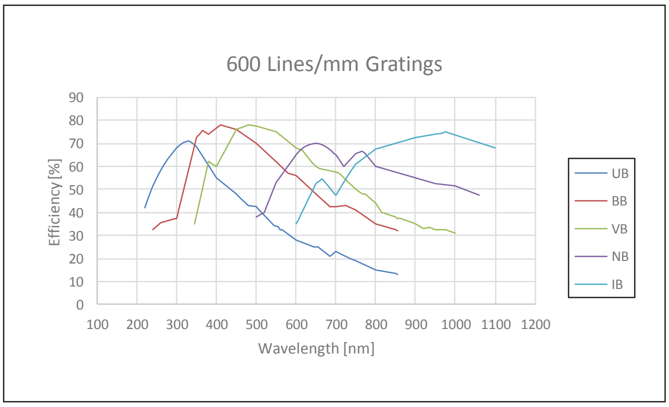
For newer types a different nomencla-ture is used stating the product line, lines/mm and blaze.

Figure 2 Grating Efficiency Curves

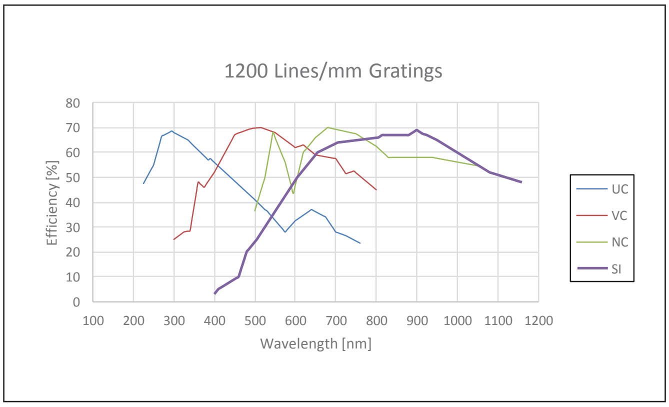
300 lines/mm gratings



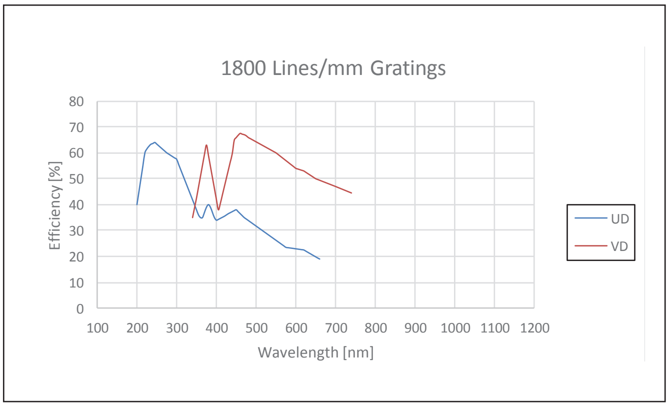
600 lines/mm gratings



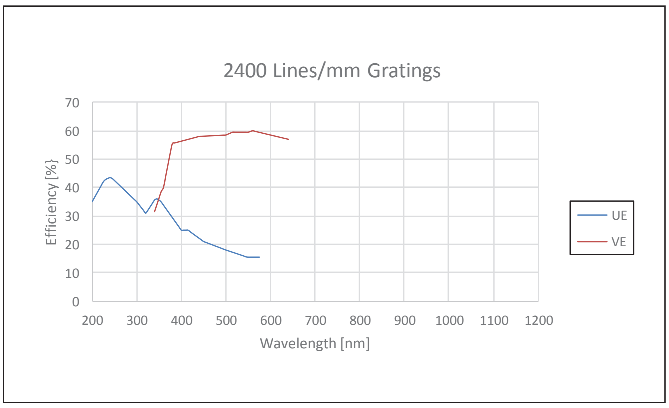
830 & 1200 lines/mm gratings



1800 lines/mm gratings



2400 lines/mm gratings



3600 lines/mm grating

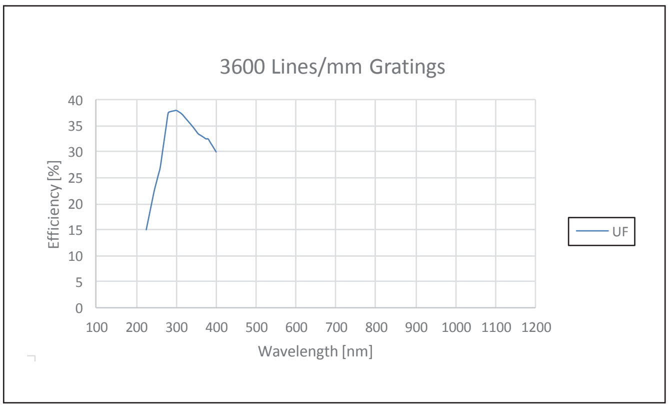
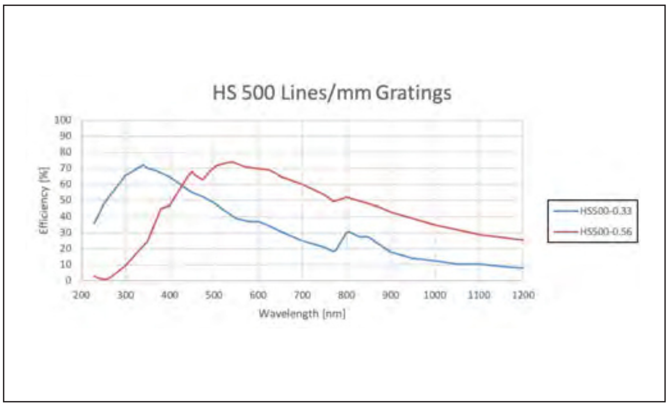
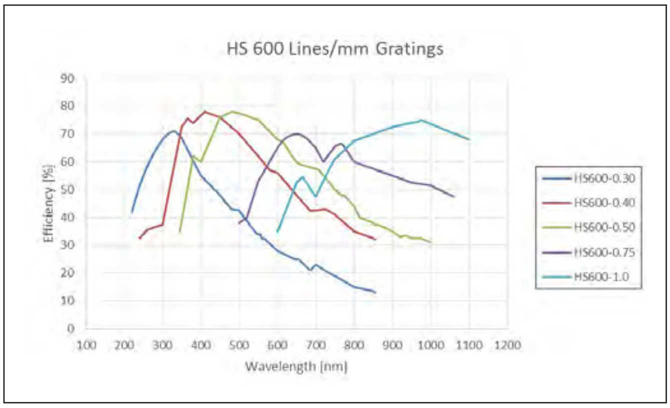


Figure 2 Grating Efficiency Curves

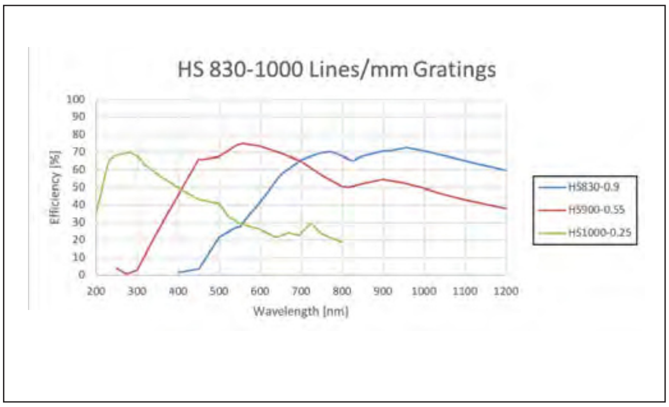
HS 500 lines/mm gratings



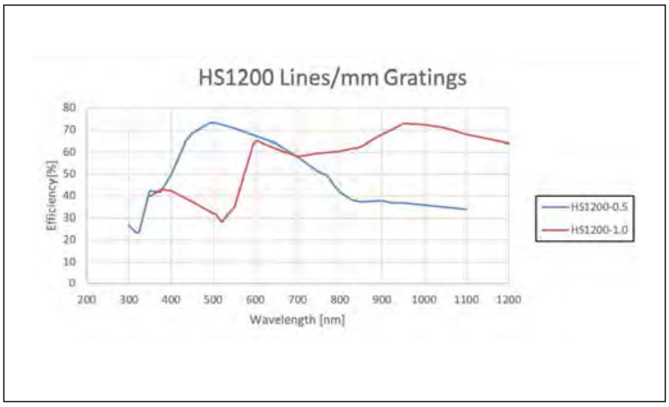
HS 600 lines/mm gratings



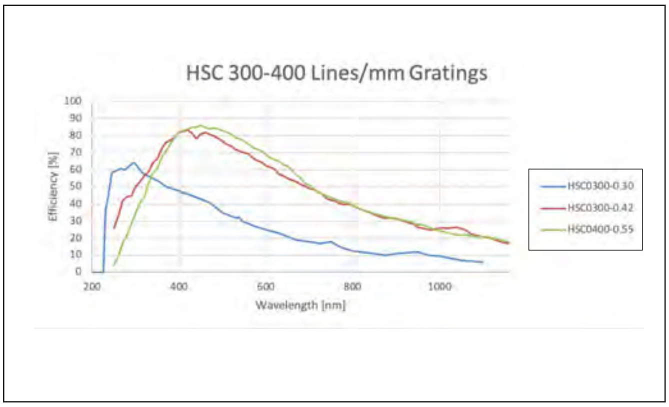
HS 830-1000 lines/mm gratings



HS 1200 lines/mm gratings



HSC 300-400 lines/mm gratings



HSC 600-830 lines/mm gratings

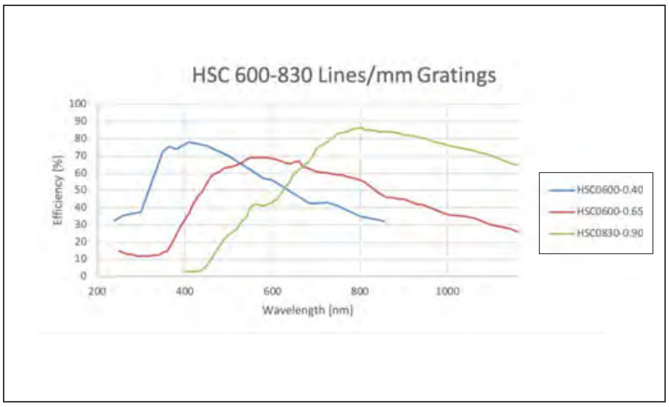
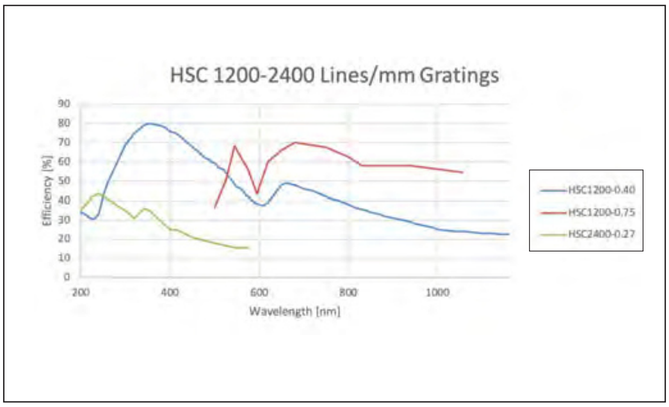
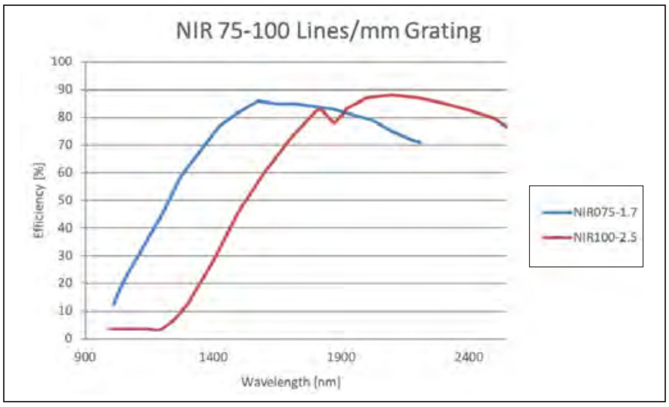


Figure 2 Grating Efficiency Curves

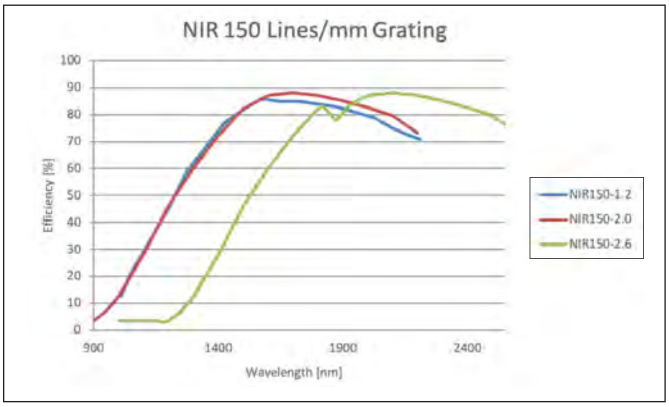
HSC 1200-2400 lines/mm gratings



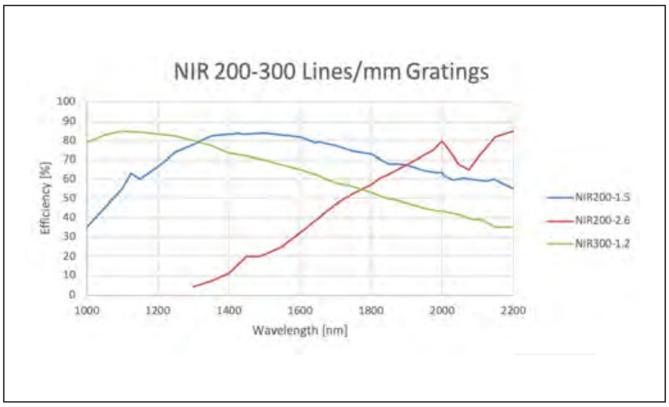
NIR 75-100 lines/mm gratings



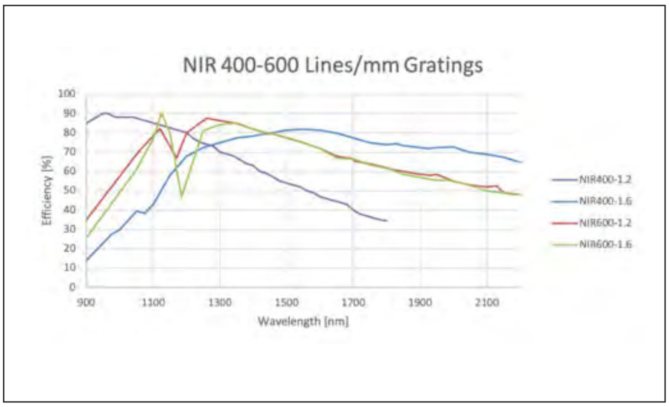
NIR 150 lines/mm gratings



NIR 200-300 lines/mm gratings

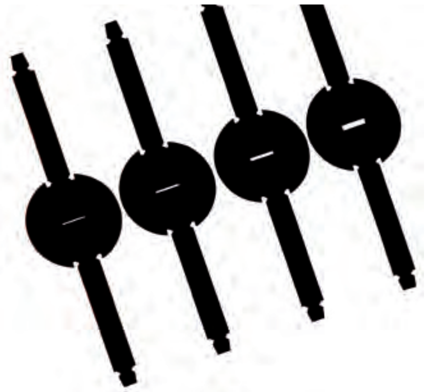


NIR 400-600 lines/mm gratings



How to select optimal optical resolution

Installed Slit in SMA Adapter



The optical resolution is defined as the minimum difference in wavelength that can be separated by the spectrometer. For separation of two spectral lines it is necessary to project them at least two array-pixels apart.

Because the grating determines how far different wavelengths are separated (dispersed) at the detector array, it is an important variable for the resolution. The other important parameter is the width of the light beam entering the spectrometer. This is basically the installed fixed entrance slit in the spectrometer, or the fiber core when no slit is installed.

For AvaSpec spectrometers the available slit widths are 5, 10, 25, 50, 100, or 200 µm wide x 1000 µm high, or 500 µm wide x 2000 µm high. The slit image on the detector array for a given wavelength will cover a number of pixels. For two spectral lines to be separated, it is necessary that they are dispersed over at least this image size plus one pixel. When large core fibers are used the resolution can be improved by a slit of smaller size than the fiber core. This effectively reduces the width of the light beam entering the spectrometer optical bench.
The influence of the chosen grating and the effective width of the light beam (fiber core or entrance slit) are shown in the tables provided for each AvaSpec spectrometer instrument.

In Table 3 the typical resolution can be found for the AvaSpec-ULS2048CL. Please note that for the higher lines/mm gratings the pixel dispersion varies along the wavelength range and improves towards the longer wavelengths.
The resolution in this table is defined as Full Width Half Maximum (FWHM), which is defined as the width in nm of the peak at 50% of the maximum intensity.

For larger pixel-height detectors (3648, 2048L, 2048CL, 2048XL, 4096CL) in combination with thick fibers (>200 µm) and a larger grating angle the actual FWHM value can be 10-20% higher than the value in the table. For best resolution small core diameter fibers are recommended.

All data in the resolution tables are based on averages of actual measured data (with 200 µm fibers) of our Quality Control System during the production process.
A typical standard deviation of 10-25%, depending on the slit diameter and the grating should be taken into account. For 10 µm slits the typical standard deviation is somewhat higher, which is inherent to the laws of physics. The peak may fall exactly within one pixel, but may cover 2 pixels causing, a lower measured resolution.

The replaceable slit feature is available on all ULS and NIR spectrometers.
The spectrometers come with one installed slit and a slit kit which includes 3 other slit sizes, so you can opt for higher resolution (25 µm slit) or higher throughput (200 µm slit) or somewhere in between (50 or 100 µm slits).

Resolution Table (FWHM in nm) for AvaSpec-ULS2048CL-EVO

	Slit size (µm)					
Grating (lines/mm)	**10**	**25**	**50**	**100**	**200**	**500**
300	1.0	1.4	2.5	4.8	9.2	21.3
600	0.40-0.53*	0.7	1.2	2.4	4.6	10.8
830	0.32	0.48	0.93	1.7	3.4	8.5
1200	0.20-0.28*	0.27-0.38*	0.52-0.66*	1.1	2.3	5.4
1800	0.10-0.18*	0.20-0.29*	0.34-0.42*	0.8	1.6	3.6
2400	0.09-0.13*	0.13-0.17*	0.26-0.34*	0.44-0.64*	1.1	2.7
3600	0.06-0.08*	0.10	0.19	0.4	0.8	1.8

* depends on the starting wavelength of the grating; the higher the wavelength, the bigger the dispersion and the better the resolution

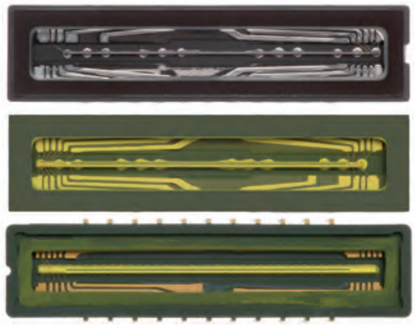
Detector arrays

The AvaSpec line of spectrometers can be equipped with several types of detector arrays. Presently we offer silicon-based CCDs, back-thinned CCDs, and CMOS Arrays for the 200-1100 nm range. A complete overview of each is given in the next section " Sensitivity " in Table 4. For the NIR range (1000-2500 nm) InGaAs arrays are implemented.

All detectors are tested in incoming goods inspection, before they are used in our instruments. Avantes offers full traceability on following detector specifications:

- Dark noise
- Signal to noise
- Photo Response Non-Uniformity
- Hot pixels

StarLine and CompactLine CMOS Detectors (2048CL/4096CL)



Both CCD (charge-coupled device) and CMOS (complementary metal-oxide semiconductor) detectors start at the same point -- they convert light into electrons, only with different technologies. In the last years CMOS sensors has improved up to a point where they reach near parity with CCD devices.

Looking to the future the CMOS detectors seem to definitely take over the standard CCD technology in general purpose spectrometers. In general the CMOS detectors have a good UV response (without the need of using UV enhancement coatings and a higher response in the NIR region.

The overall sensitivity tends to be somewhat lower than with the CCD technology.

SensLine Back-thinned CCD Detectors (2048XL/2048x64/1024x58)

For applications requiring high quantum efficiency in the UV (200-350 nm) and NIR (900-1160 nm) range, combined with good S/N and a wide dynamic-range, back-thinned CCD detectors are the right choice.

Avantes offers cooled and uncooled versions. In case of a 2D-detection the vertical pixels are binned, giving effectivly one high pixel to increase sensitivity.

\+ Advantage of the back-thinned CCD detector is the good UV and NIR sensitivity, combined with good S/N and dynamic range.

\- Disadvantage is the relatively higher cost.

NIRLine InGaAs linear image sensors (AvaSpec-NIR256/512)

The InGaAs linear image sensors deliver high-sensitivity in the NIR wavelength range. The detector consists of a charge-amplifier array with CMOS transistors, a shift-register and timing generator. For InGaAs detectors the dynamic range is limited by the dark noise. For ranges up to 1.75 µm no cooling is required and these detectors are available in both 256 and 512 pixels. Detectors for the extended range -2.5 µm all have 2- stage TE-cooling to reduce dark noise and are available in 256 and 512 pixel versions.

6 versions of detectors are available:

- 256/512 pixel non-cooled InGaAs detector for the 900-1750 nm range
- 256/512 pixel cooled InGaAs detector for the 900-1750 nm range
- 256/512 pixel 2-stage cooled Extended InGaAs detector for the 1000-2500 nm range

Sensitivity

The sensitivity of a detector pixel at a certain wavelength is defined as the detector electrical output per unit of radiation energy (photons) incident to that pixel. With a given A/D converter this can be expressed as the number of counts per mJ of incident radiation.

The relation between light energy entering the optical bench and the amount hitting a single detector pixel depends on the optical bench configuration. The efficiency curve of the grating used, the size of the input fiber or slit, the mirror performance and the use of a Detector Collection Lens are the main parameters. With a given set-up it is possible to do measurements over about 6-7 decades of irradiance levels. Some standard detector specifications can be found in Table 4 detector specifications. Optionally, a cylindrical detector collection lens (DCL) can be mounted directly on the detector array.

The DCL-UV/VIS-200 can be used for our spectrometers with larger pixel heights to have a better vertical distribution of light focusing on the detector and is primarily for fiber diameters larger than 200 µm and round- to-linear assemblies.
Our SensLine has the most sensitive detectors out of all of our instrument lines, as it includes back-thinned and thermoelectrically cooled detectors.

In Table 4 the UV/VIS detectors are depicted with their specifications, please find below some additional information on how those specifications are determined.

Pixel Well Depth (electrons)

This value is specified by the detector supplier and defines how many electrons can fit in a pixel well before it is saturated, this value determines the best reachable Signal to Noise (=√(Pixel well depth)).

Sensitivity in Photons/count @ 600 nm

The number of Photons of 600 nm that are needed to generate one count of signal on a 16-bit AD converter, the lower this number is, the better is the sensitivity of the detector.

The calculation of the number of Photons/count is (Pixel Well depth in electrons)/16-bit AD/Quantum Efficiency @ 600 nm.

Sensitivity in counts/µW per ms integration time

Sensitivity here is for the detector types currently used in the UV/VIS AvaSpec spectrometers as output in counts per ms integration time for a 16-bit AD converter. To compare the different detector arrays we have them all built up with an optical bench with UA 300 lines/mm grating covering 200-1100 nm, DCL if applicable, and 50 µm slit.

The measurement setup for 350-1100 nm has a 600 µm fiber connected to an AvaSpere-50-LS-HAL, equivalent to an optical power of 1.14 µW.

For the UV/VIS measurement at 220-1100 nm we connected the 600 µm fiber to an AvaLight-DHS through a CC-VIS/NIR diffuser, equivalent to 2.7 µW power.

Peak Wavelength and QE @ peak

The peak wavelength is provided by the detector supplier as well as the Quantum Efficiency, defined as the number of electrons generated by one photon.

Signal/Noise

Signal/Noise is measured for every detector at Avantes' Quality Control Inspection and defined as the illuminated maximum Signal/ Noise in Root Mean Square for the shortest integration time. The RMS is calculated over 100 scans.

Dark Noise

Dark noise is measured for every detector at Avantes' Quality Control Inspection and defined as the non-illuminated noise in

Root Mean Square for the shortest integration time. The RMS is calculated over 100 scans.

Dynamic Range

The dynamic range is defined as the (maximum signal level- baseline dark level)/dark noise RMS.

Photo Response Non-Uniformity

Photo Response Non-Uniformity is defined as the max difference between output of pixels when uniformly illuminated, divided by average signal of those pixels.
PRNU is measured for every detector at Avantes' Quality Control Inspection.

Frequency

The frequency is the clock frequency at which the data pixels are clocked out through the AD-converter.

Table 4 Detector Specifications (based on a 16-bit AD converter)

	StarLine			SensLine			
Detector	HAM-2048CL	HAM-4096CL	SONY-2048L	HAM-2048XL	HAM-2048x64TEC	HAM-2048x64	HAM-1024x58
Type	CMOS linear array	CMOS linear array	CCD linear array	Back-thinned CCD array	Cooled Back-thinned CCD array	Back-thinned CCD array	Cooled Back-thinned CCD array
# Pixels, pitch	2048, 14 µm	4096, 7 µm	2048, 14 µm	2048, 14 µm	2048, 14 µm	2048, 14 µm	1024 x 58, 24 µm
Pixel width x height (µm)	14 x 200	7 x 200	14 x 200	14 x 500	14 x 14 (total height 0.9 mm)	14 x 14 (total height 0.9 mm)	24 x 24 (total height 1.4 mm)
Pixel well depth (electrons)	80,000	80,000	90,000	200,000	300,000	200,000	1,000,000
Sensitivity Photons/ count @600 nm	2	2	2	4	6	4	16
Sensitivity in counts/µW per ms integration time	375,000 (AvaSpec-ULS2048CL)	218,000 (AvaSpec-ULS4096CL)	470,000 (AvaSpec-ULS2048L)	460,000 (AvaSpec-ULS2048XL)	300,000 (AvaSpec-ULS2048x64 TEC)	650,000 (AvaSpec-ULS2048x64)	445,000 (AvaSpec-HERO)
Peak wavelength	700 nm	700 nm	450 nm	650 nm	600 nm	600 nm	650 nm
QE (%) @ peak	80%	80%	40%	78%	78%	78%	92%
Signal/Noise	300:1	335:1	300:1	525:1	550:1	450:1	1200:1
Dark noise (counts RMS)	16	16	20	5	5	11.5	2
Dynamic Range	4000	4000	3300	13,700	19,000	1600	40,000
PRNU*	± 5%	± 5%	± 5%	± 3%	± 3%	± 3%	± 3%
Wavelength range (nm)	200-1100	200-1100	200-1100	200-1160	200-1160	200-1160	200-1160
Frequency	6 MHz	6 MHz	2 MHz	1 MHz	500 kHz	1.33 MHz	250 kHz

* Photo-Responsive Non-Uniformity

Figure 3a Sensitivity Curve StarLine

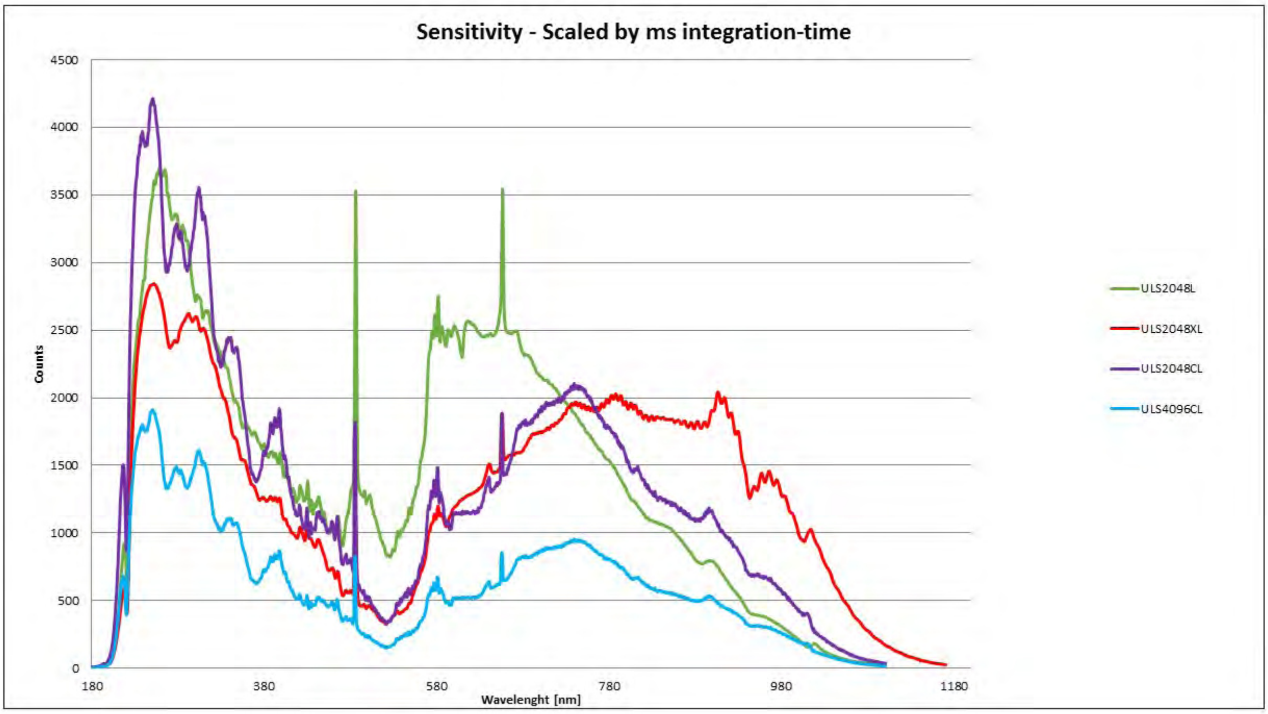
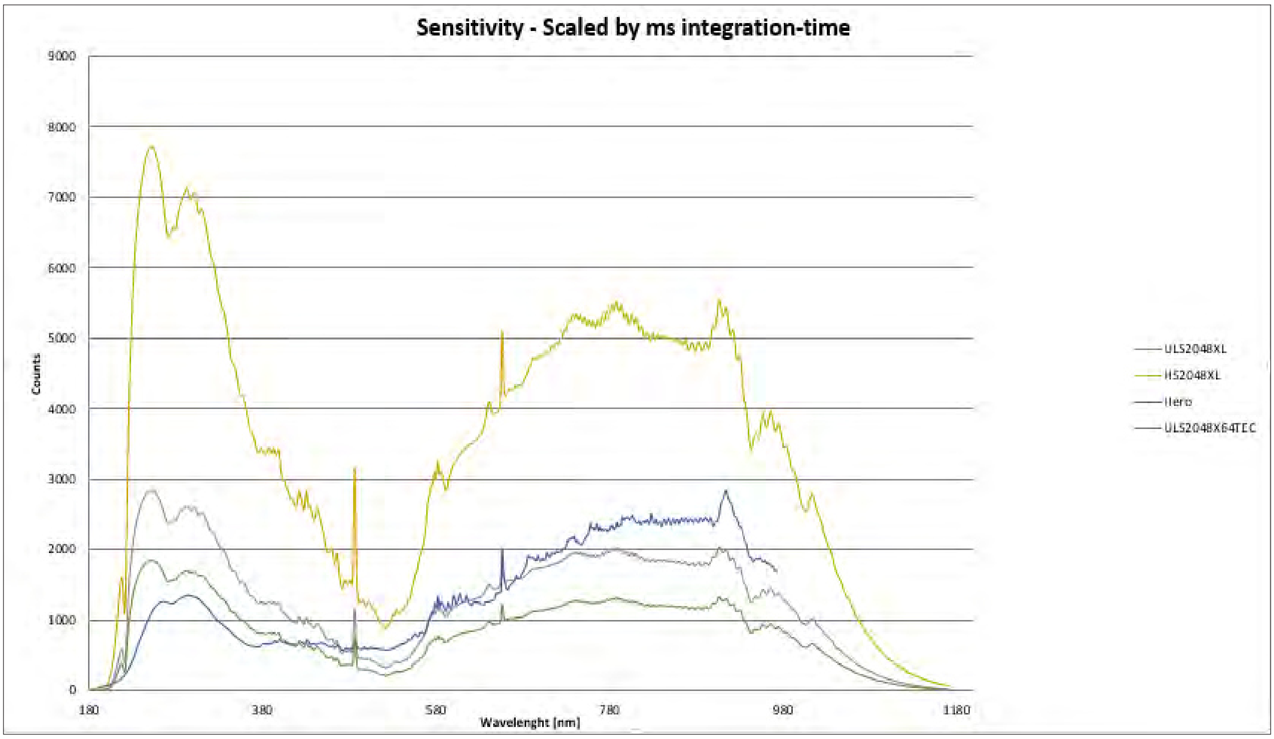


Figure 3b Sensitivity Curve SensLine



In Table 5 the specifications for the NIR spectrometers are given.

Sensitivity

For NIR detectors 2 different modes are available, the default setting is for high-sensitivity mode (HS), this means more signal at a shorter integration time.

The other mode of operation is low-noise (LN), this means a better S/N performance. Sensitivity, S/N, dark noise and Dynamic Range are given as HS and LN values.

Table 5 Detector Specifications (AvaSpec-NIR Models)

	NIRLine					
Detector	HAM-256-1.7	HAM-512-1.7	SU-256-1.7	SU-512-1.7	HAM-256-2.5	HAM-512-2.5
Type	Linear InGaAs array	Linear InGaAs array	Linear InGaAs array with 1-stage TE cooling	Linear InGaAs array with 1-stage TE cooling	Linear InGaAs array with 2-stage TE cooling	Linear InGaAs array with 2-stage TE cooling
# Pixels, pitch	256, 50 µm	512, 25 µm	256, 50 µm	512, 25 µm	256, 50 µm	512, 25 µm
pixel width x height (µm)	50 x 500	25 x 500	50 x 500	25 x 500	50 x 250	25 x 250
Sensitivity HS in counts/µW per ms	8,200,000 (integral 1000-1750 nm)	3,880,000 (integral 1000-170 nm)	4.800,000 (integral 1000-1750 nm)	2.500,000 (integral 1000-1750 nm)	990,000 (integral 1000-2500 nm)	480,000 (integral 1000-2500 nm)
Signal/Noise (HS)	1900:1	1900:1	1900:1	1900:1	1800:1	1900:1
Dark noise HS (counts RMS)	16	16	16	16	16	15
Dynamic Range HS	6000	6000	4900	4900	3500	4300
Sensitivity LN in counts/µW per ms	469,000 (integral 1000-1750 nm)	222,000 (integral 1000-1750 nm)	160,000 (integral 1000-1750 nm)	83,000 (integral 1000-1750 nm)	55,000 (integral 1000-2500 nm)	26,600 (integral 1000-2500 nm)
Signal/Noise (LN)	5000:1	5000:1	5000:1	5000:1	4000:1	3700:1
Dark noise LN (counts RMS)	12	12	12	12	12	13
Dynamic Range LN	9000	9000	7600	7600	4500	5100
Peak wavelength	1550 nm	1550 nm	1500 nm	1500 nm	2300 nm	2300 nm
QE (%) @ peak	90%	90%	70%	70%	65%	65%
PNRU**	±5%	±5%	10%	10%	±5%	±5%
Defective pixels (max)	0	0	0	0	12	26
Wavelength range (nm)	900-1750	900-1750	900-1750	900-1750	1000-2500	1000-2500
Frequency	500 kHz	500 kHz	1.2 MHz	1.2 MHz	500 kHz	500 kHz

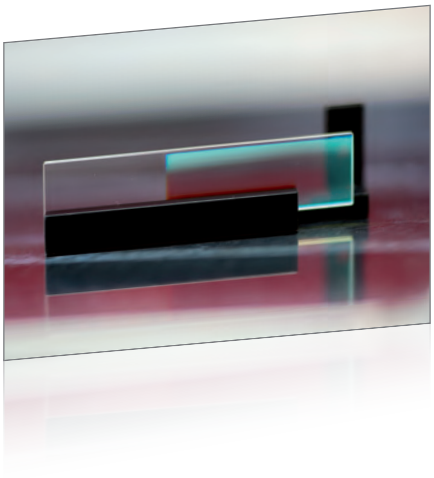
*** Photo-Response Non-Uniformity*

Stray light and second-order effects

Stray-light is radiation of undesired wavelengths that activates a signal at a detector element. Sources of stray-light can be:

- *Ambient light*
- *Scattering light from imperfect optical components, or reflections of non-optical components*
- *Order overlap*

Order-Sorting Window in holder



Avantes symmetrical Czerny-Turner optical bench designs favor stray-light rejection relative to crossed designs. Additionally, Avantes Ultra-Low Stray-light (AvaSpec-ULS) spectrometers have a number of internal measures to reduce stray-light from zero order and backscattering.

When working at the detection limit of the spectrometer system, the stray-light level from the optical bench, grating and focusing mirrors will determine the ultimate limit of detection. Most gratings used are holographic gratings, known for their low level of stray-light. Stray-light measurements are conducted using a halogen light source and long-pass or band-pass filters.

Typical stray-light performance for the AvaSpec-ULS and a B-type grating is <0.06% at 250-500 nm. Second order effects, which can play an important role for gratings with low groove frequency, and therefore a wide wavelength range, are usually caused by the 2nd order diffracted beam of the grating. The effects of these higher orders sometimes need to be addressed using filtering. The strategy is to limit the light to the region of the spectra, where order overlap is not possible.

Second order effects can be filtered out, using a permanently installed long-pass optical filter in the SMA entrance connector or an order-sorting coating on a window in front of the detector. The order-sorting coatings on the window typically have one long-pass filter (600 nm) or 2 long-pass filters (350 nm and 600 nm), depending on the type and range of the selected grating. In the broadband ULS configurations, Linear Variable Filters are used for even better suppression of the second order effects.

In Table 6, a wide range of optical filters for installation in the optical bench can be found. The filter types that are 3 mm thick give a much better 2nd order reduction than the 1 mm filters. The use of following long-pass filters is recommended: OSF-475 for grating NB and NC, OSF-515 / 550 for grating NB and OSF-600 for grating IB. For backthinned detectors, such as the 2048XL and 1024x58/122 we recommend an OSF-305 Filter, when the starting wavelength is 300 nm and higher.

Table 6 Filters installed in AvaSpec spectrometer series

OSF-XXX	Permanently installed order-sorting filter @ XXX nm (XXX= 305, 395, 475, 515, 550, 600, 850)
OSC	Order-sorting coating with 600 nm long-pass filter for BB (>350 nm) and VB gratings
OSC-UA	Order-sorting coating with 350 and 600 nm long-pass filter for UA/VA gratings. Linear Variable Filter for ULS benches
OSC-UB	Order-sorting coating with 350 and 600 nm long-pass filter for UB or BB (<350 nm) gratings
OSC-UC	Order-sorting coating with 300 nm long-pass filter for UC gratings
OSC-HS500	Order-sorting coating with 350 and 600 nm long-pass filter for HS500 gratings in AvaSpec-HS
OSC-HS900	Order-sorting coating with 600 nm long-pass filter for HS900 gratings in AvaSpec-HS
OSC-HS1000	Order-sorting coating with 350 nm long-pass filter for HS1000 gratings in AvaSpec-HS
OSC-HSC300	Order-sorting coating for use with grating HSC0300-xx
OSC-HSC600	Order-sorting coating for use with grating HSC0600-xx
OSC-NIR	Order-sorting coating with 1400 nm long-pass filter for NIR100-2.5 and NIR150-2.0 gratings in AvaSpec-NIR256/512-2.5TEC