Spectral Performance of WFIRST/AFTA Bandpass Filter Prototypes

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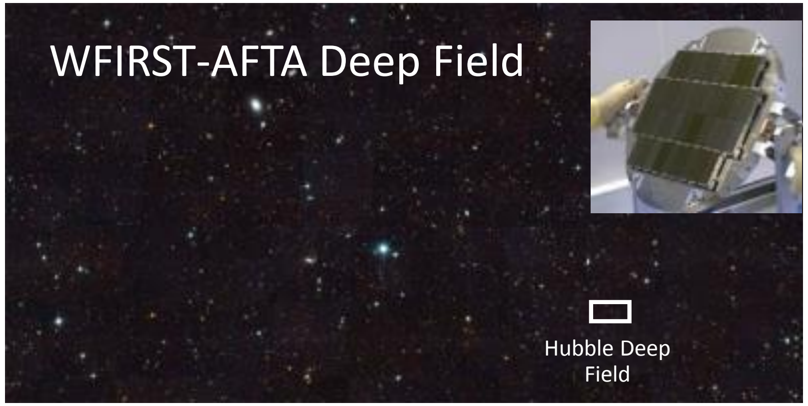
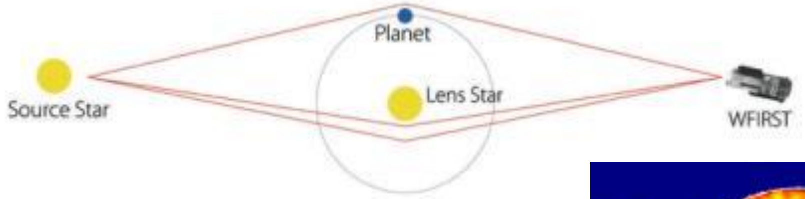
Outline

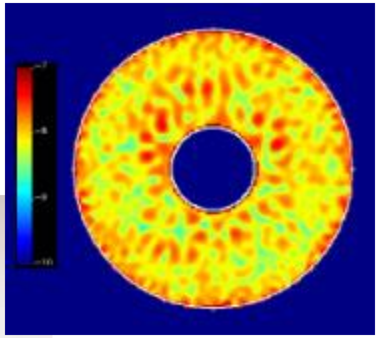
- Overview & Objectives
- Experimental details
- Results
- Conclusions

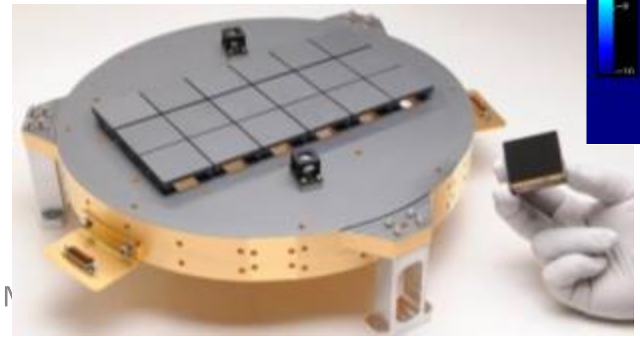
WFIRST-AFTA Summary

- The highest ranked NWNH large space mission.
- Dark energy that is driving the current accelerating expansion of the universe
  - A wide field telescope for pointed wide observations of the NIR sky
  - Perform statistical census of planetary systems through microlensing survey
- The WFIRST-AFTA Design Reference Mission has
  - 2.4 m telescope (already exists)
  - NIR instrument with 18 H4RG HgCdTe detectors
  - Baseline exoplanet coronagraph
  - 5 year lifetime, 10 year goal
- WFIRST-AFTA will perform Hubble-like quality and depth imaging with a much larger field of view



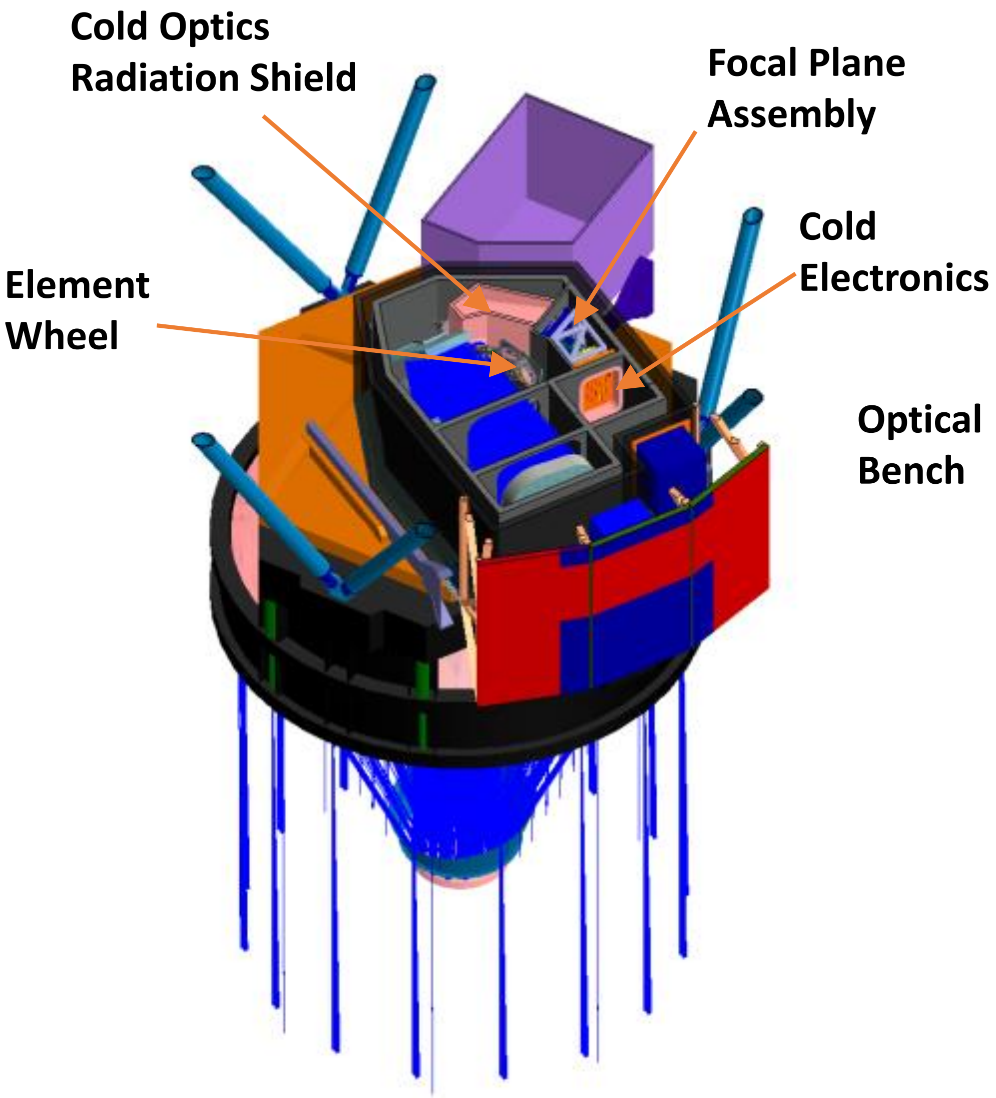




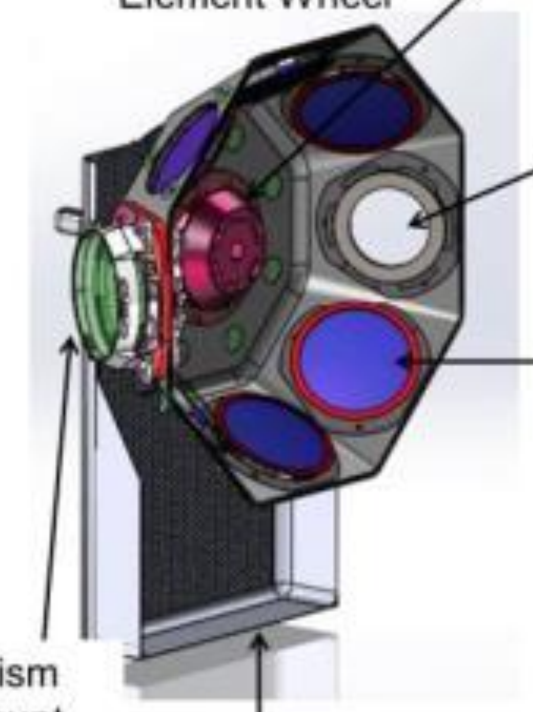


Key Features

- Single wide field channel instrument for both imaging and spectroscopy
  - 3 mirrors, 1 powered
  - 18 4K x 4K HgCdTe detectors
  - 0.11 arc-sec plate scale
  - Grism used for GRS survey
- IFU channel for SNe spectra, single HgCdTe detector
- Single element wheel for filters and Grism



Element Wheel Assembly



Wide Field Channel Description (Cycle 5)

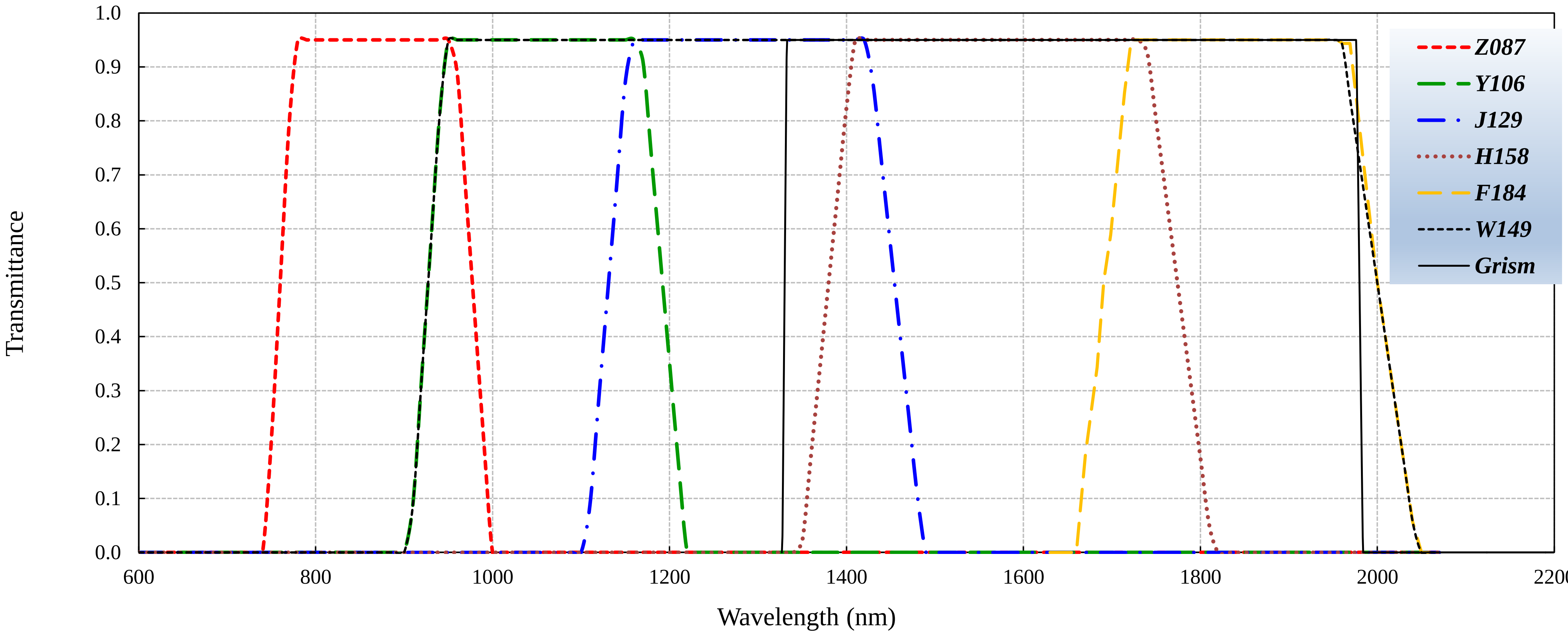
- The wide field channel's only routinely moving part is the element wheel (EW)
- 8 positions: 6 filters, blank, grism (galaxy redshift survey)
- Table shows how measurement modes and observations align

				SN Detect		SN Spec	HLS		Microlensing		Avail for GO
#	Min (mm)	Max (mm)	R	Shallow	Med/Deep		Image	Spec	Monitor	Color	
Z087	0.760	0.977	4.0							2X daily	
Y106	0.927	1.192	4.0	X			Photo-z				
J129	1.131	1.454	4.0	X	X						
H158	1.380	1.774	4.0		X		Photo-z & Shapes				
F184	1.683	2.000	5.81								All
W149	0.927	2.000	1.442					X	15 min cadence		
GRS	1.35	1.95	793								
IFU	0.600	2.000	75			X					

#	Min (mm)	Max (mm)	Center (mm)	Width (mm)	R
Z087	0.760	0.977	0.869	0.217	4
Y106	0.927	1.192	1.060	0.265	4
J129	1.131	1.454	1.293	0.323	4
H158	1.380	1.774	1.577	0.394	4
F184	1.683	2.000	1.842	0.317	5.81
W149	0.927	2.000	1.485	1.030	1.44
GRS	1.35	1.95	1.650	0.600	2. 75

WFI element wheel optics list

Spectral Band-Pass Definitions

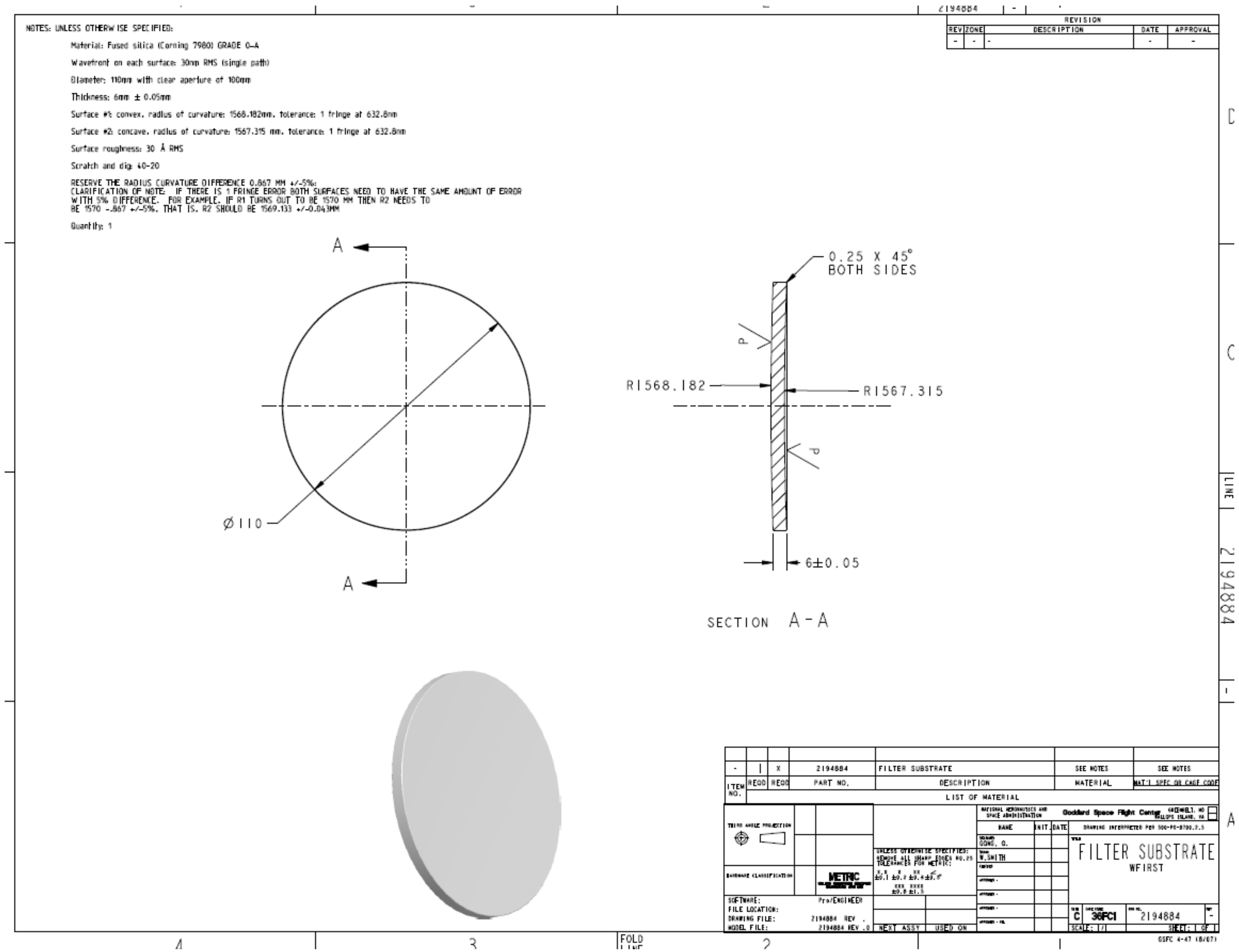


Objectives

- Procurement of a subset WFI filter complement:
  - Grism (**Tight slope requirement**)
  - W149 (**Widest band**)
  - Z087 (**Shorter passband**)
- Spectral and interferometric characterizations:
  - Band-pass transmission performance at various temperatures, particularly @ ***170K*** , the operating temperature for WFIRST.
  - Spatial Uniformity
  - Out-of-band rejection
  - Reflected Wave Front Error Distortion
- Report to WFIRST design team.

Filter Substrate Requirements

- Flat substrate disks (110 mm x 6mm) of the Corning 7980 type.
- Relatively tight WFE performance (<0.5 wave @ 632.8 nm).
- Substrates were sent to all 3 vendors (3 EA) for bandbass coating application.
- One inch coupons were also requested (for cryogenic measurement purposes)
- Three coating vendors were selected (labeled **A, B, and C**) to produce prototypes for each of the 3 filters:

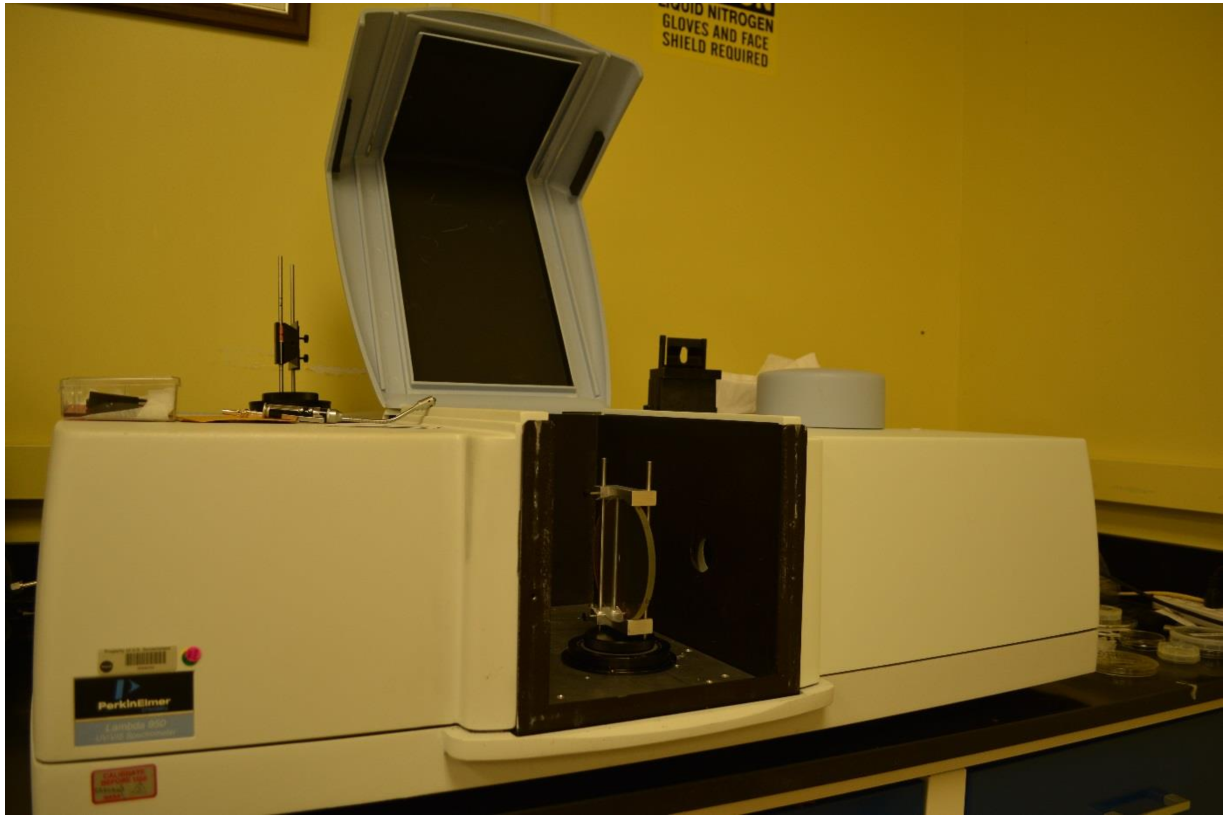


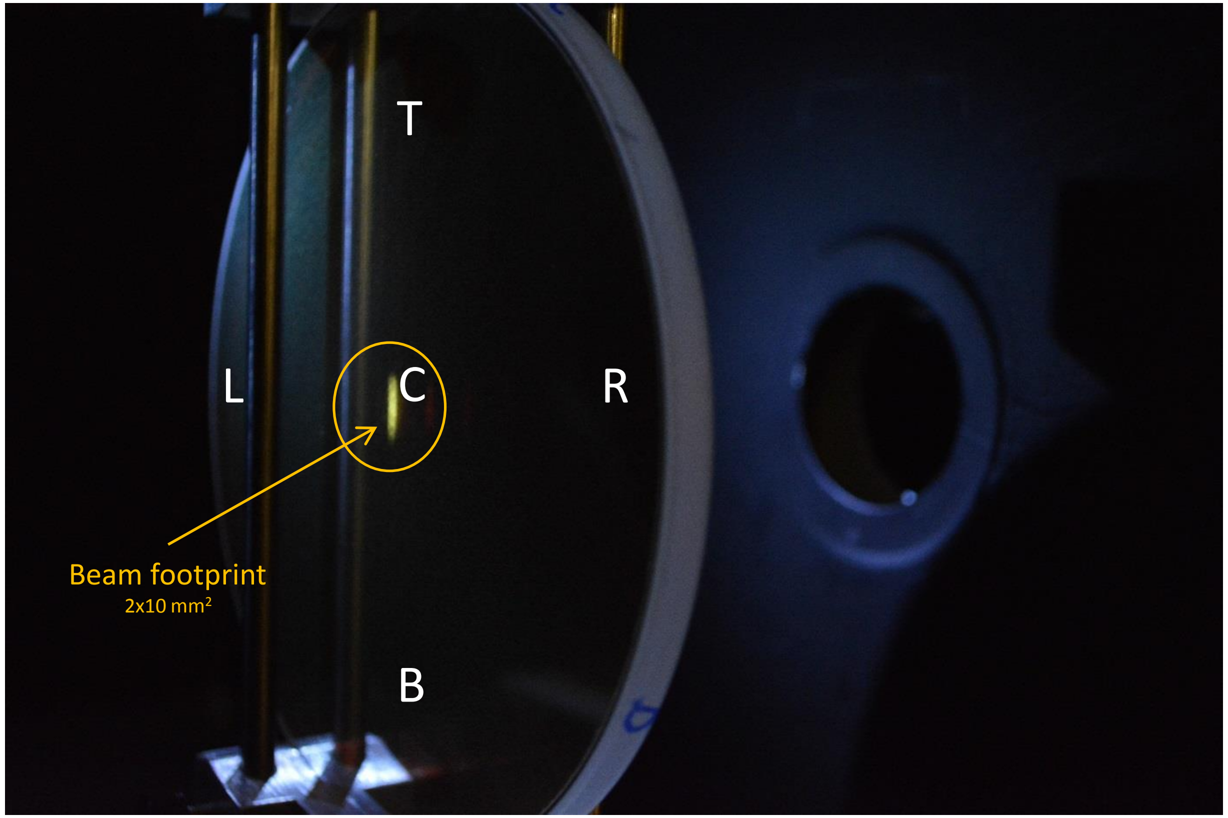
Spectral Characterization

Perkin Elmer Spectrometer (950)

Transmittance > 200-3000 nm spectral range (Spectral resolution 0.25 nm)
Photometric accuracy (8A units)

Spectral uniformity





Cryogenic Measurements

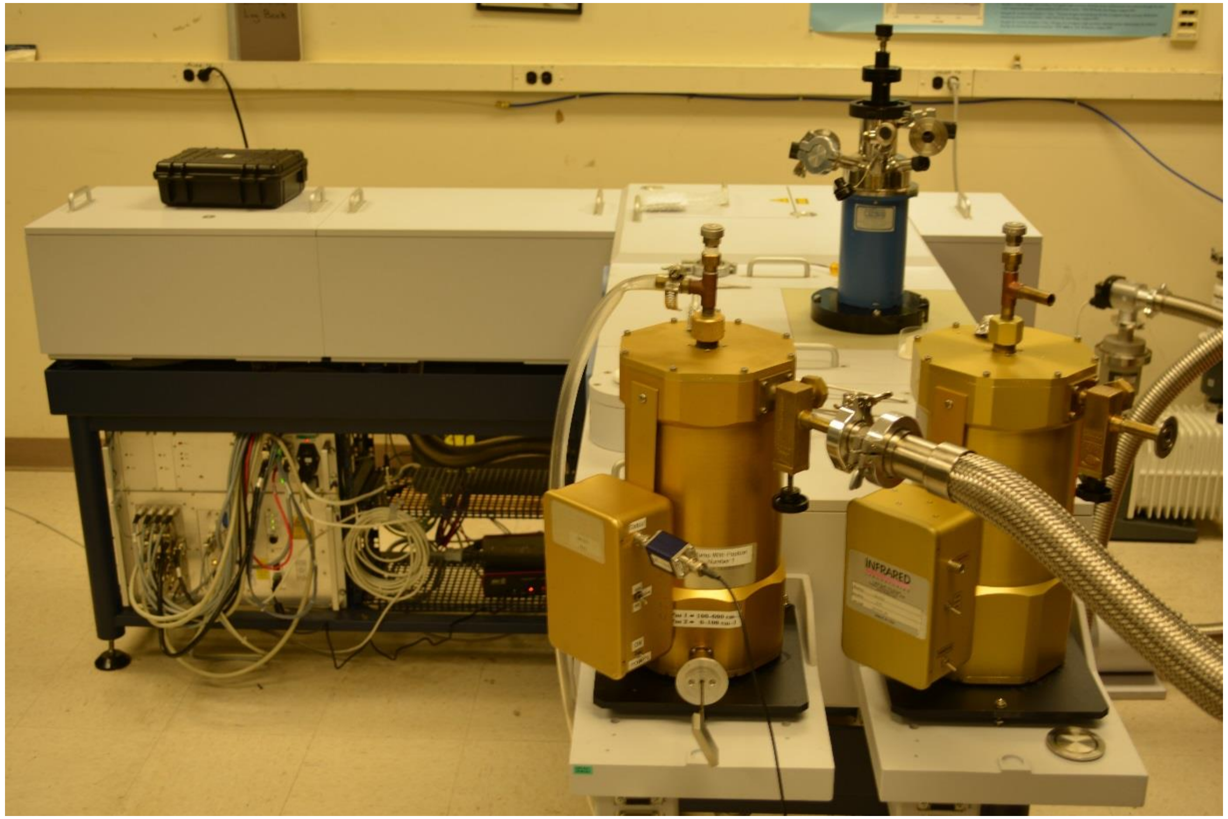
Bruker Spectrometer

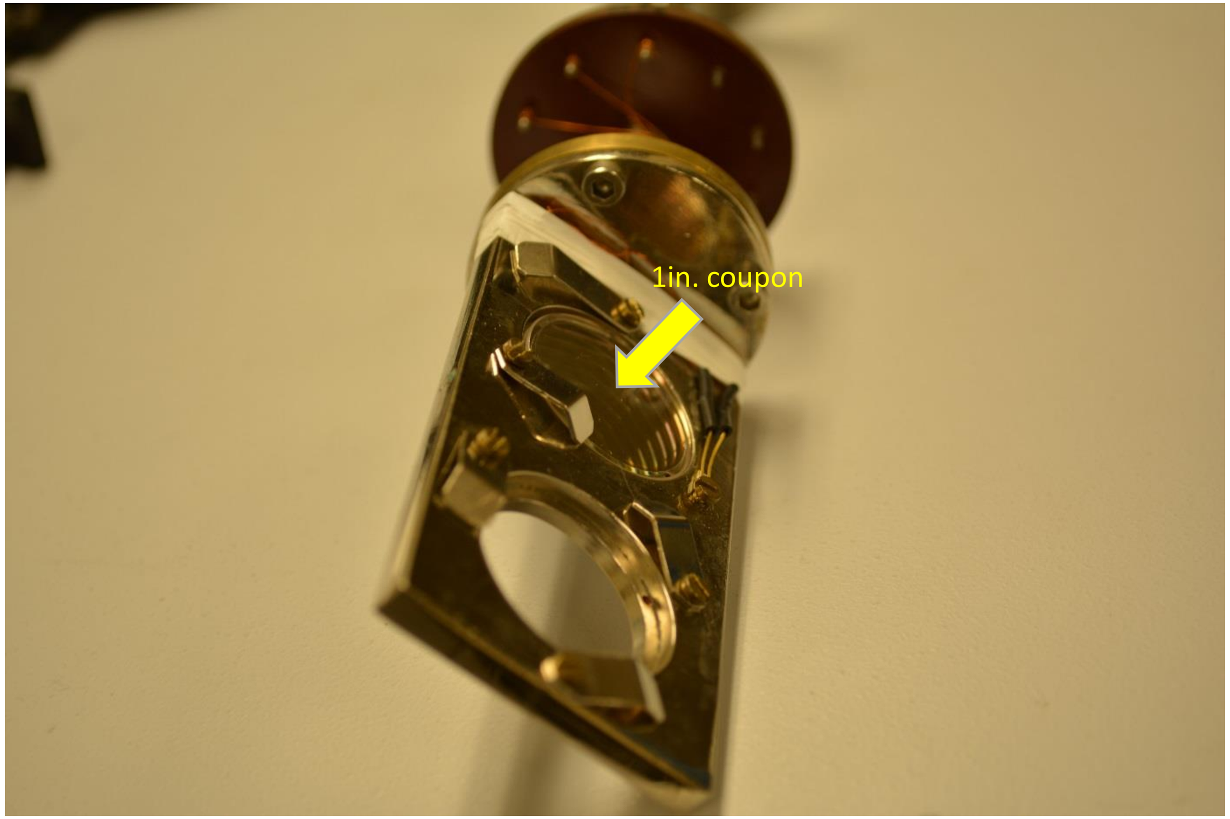
Fourier Transform Spectrometer (FTS)

1000-10000 nm (Res. < 0.05 nm)

Photometric accuracy (3-4A)

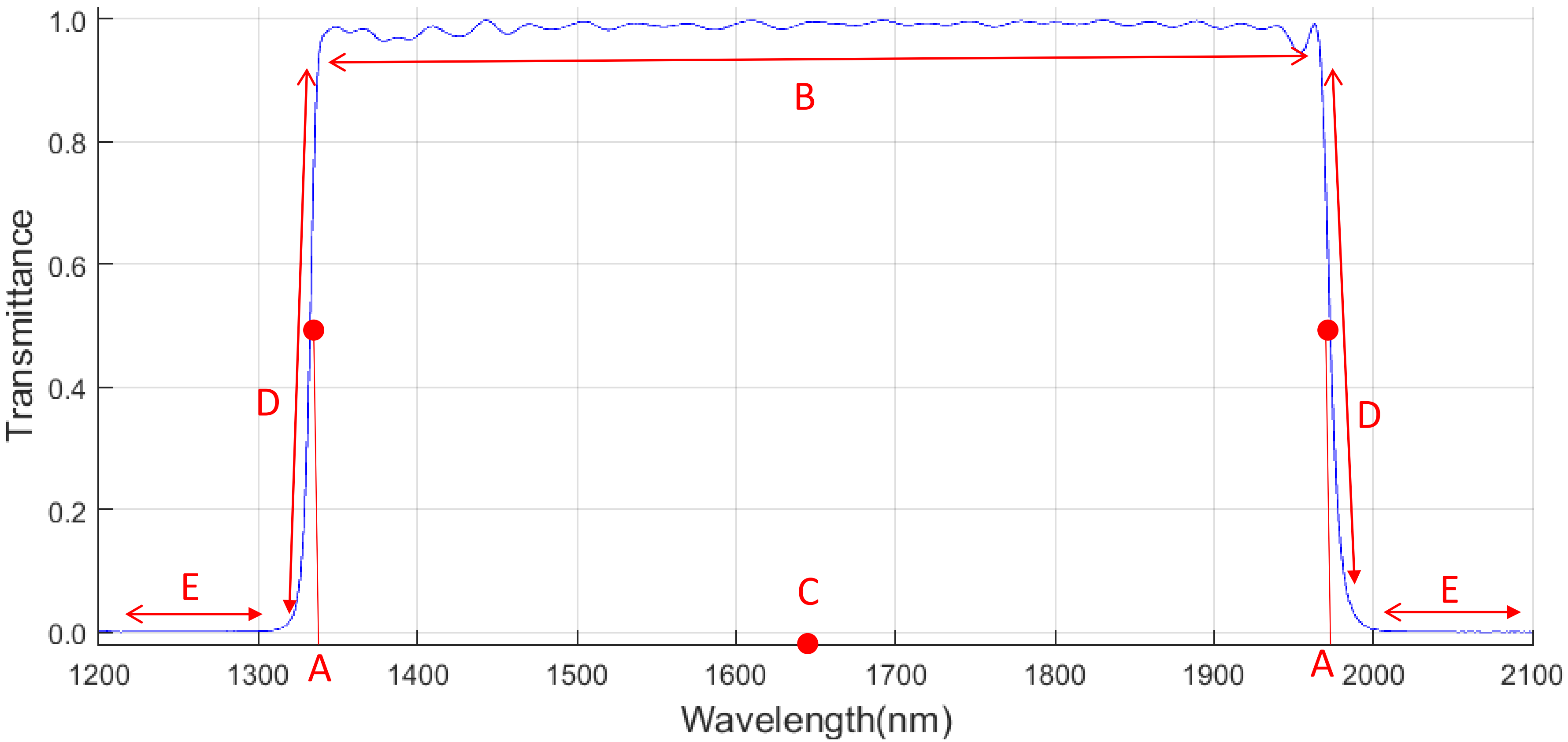
Cryostat Sample holder





Band-Pass Filter Parameters

For a given transmission curve, the followings are the characteristics we are interested in:



A: Wavelengths @ 50%T_IB

B: Ave. In-band Transmission

C: Center Wavelength

$W_C = (W_{@50\%T\_H} + W_{@50\%T\_L})/2$

D: Slope of the edges

$Slope = |W_{@90\%T} - W_{@10\%T}|/W_{@50\%T}$

E: Ave.Out-of-band optical density

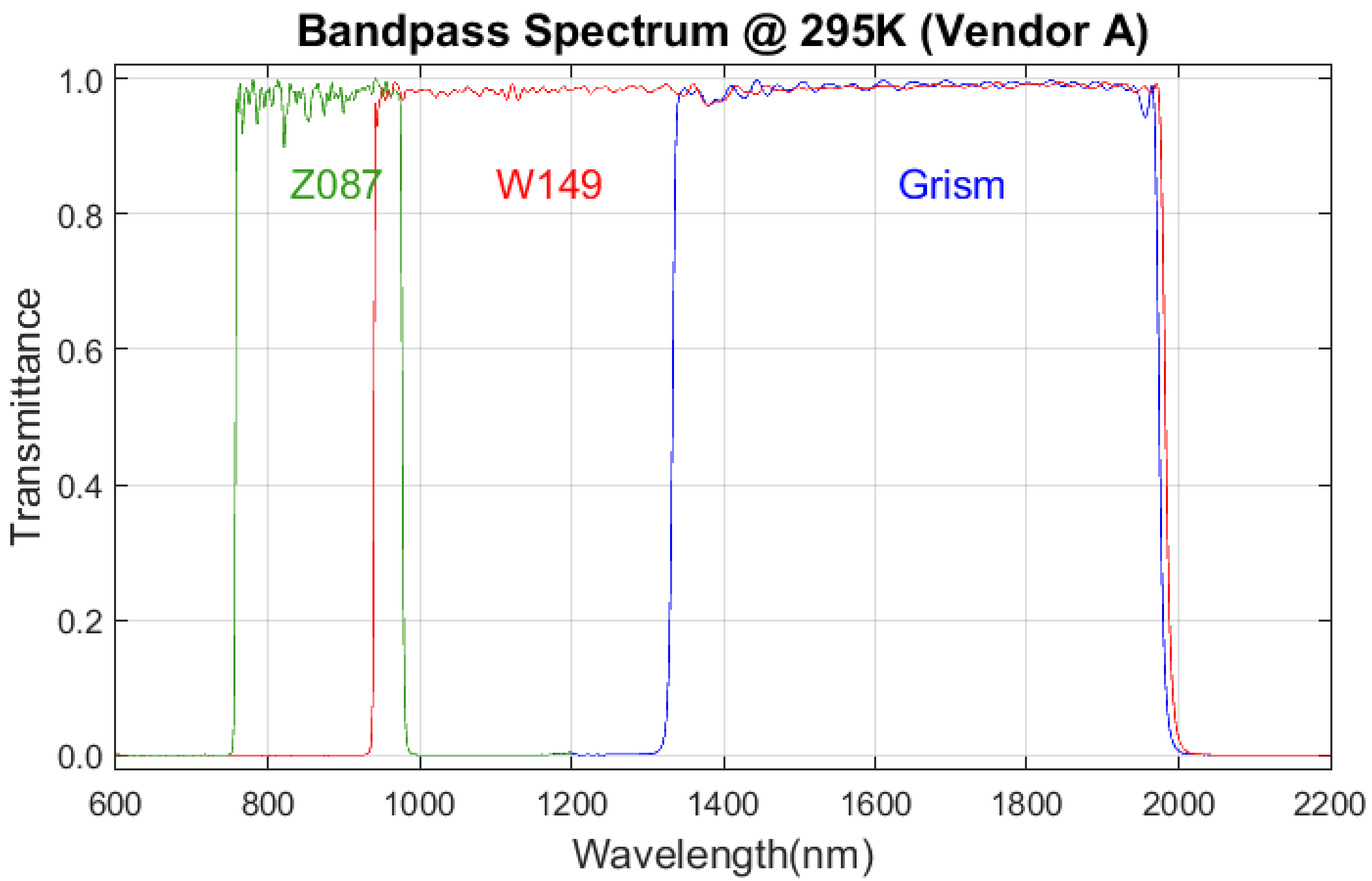
Opt_Den = -log10(Transmittance)

Band-Pass Filter Parameters cont…

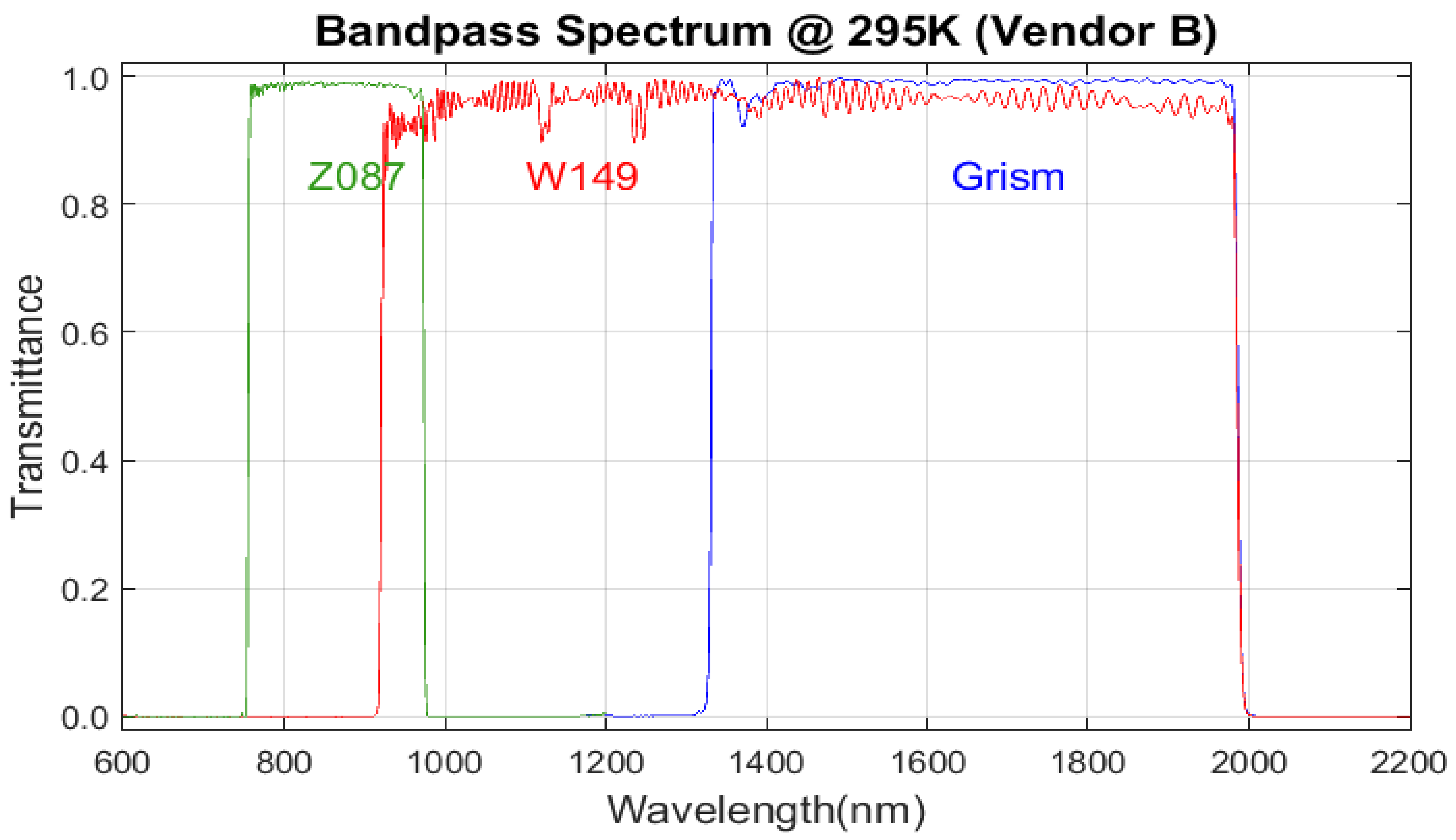
	BANDPASS REQUIREMENTS (Cycle5)		
Parameter	Grism	Z087	W149
A	$\geq$ 95%	$\geq$ 95%	$\geq$ 93%
B_S	1345 nm (±5 nm)	758 nm (±10 nm)	925 nm (±20 nm)
B_L	1955 nm (±5 nm)	978 nm (±10 nm)	2000 nm (±20 nm)
C	1650 nm (±5 nm)	868 nm (±10 nm)	1462 nm (±20 nm)
D_S, D_L	$\leq$ 0.2%	$\leq$ 3%	$\leq$ 3%
E_S	OD 4 (500-1250 nm)	OD 4 (500-740 nm)	OD 4 (500-900 nm)
E_L	OD 5 (2050-3000 nm)	OD 5 (1000-3000 nm)	OD 5 (2050-3000 nm)

Spectrum Overview: Vendor A

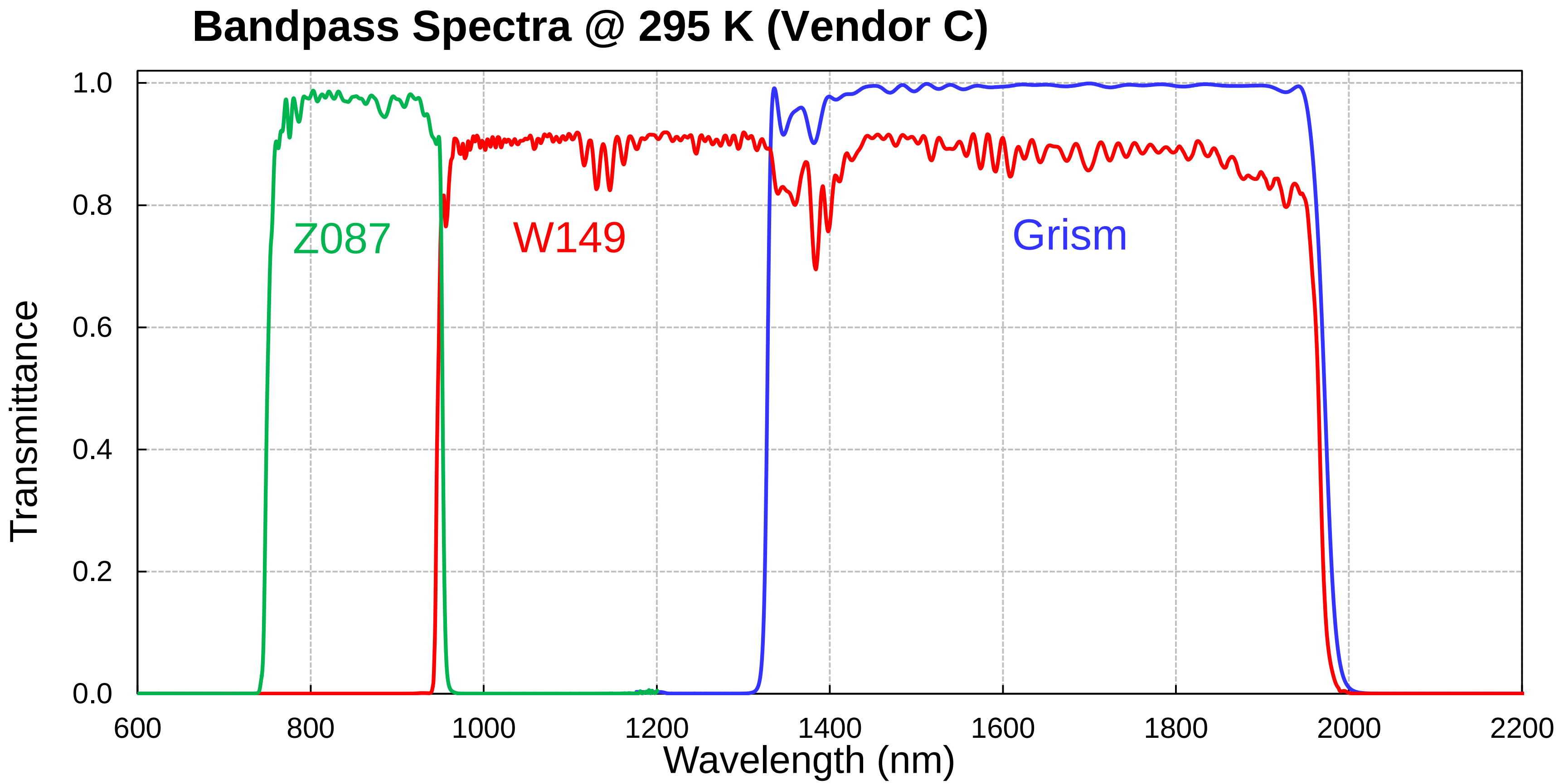
3 types of filters (Grism, W149, and Z087):



Spectrum Overview: Vendor B



Spectrum Overview: Vendor C

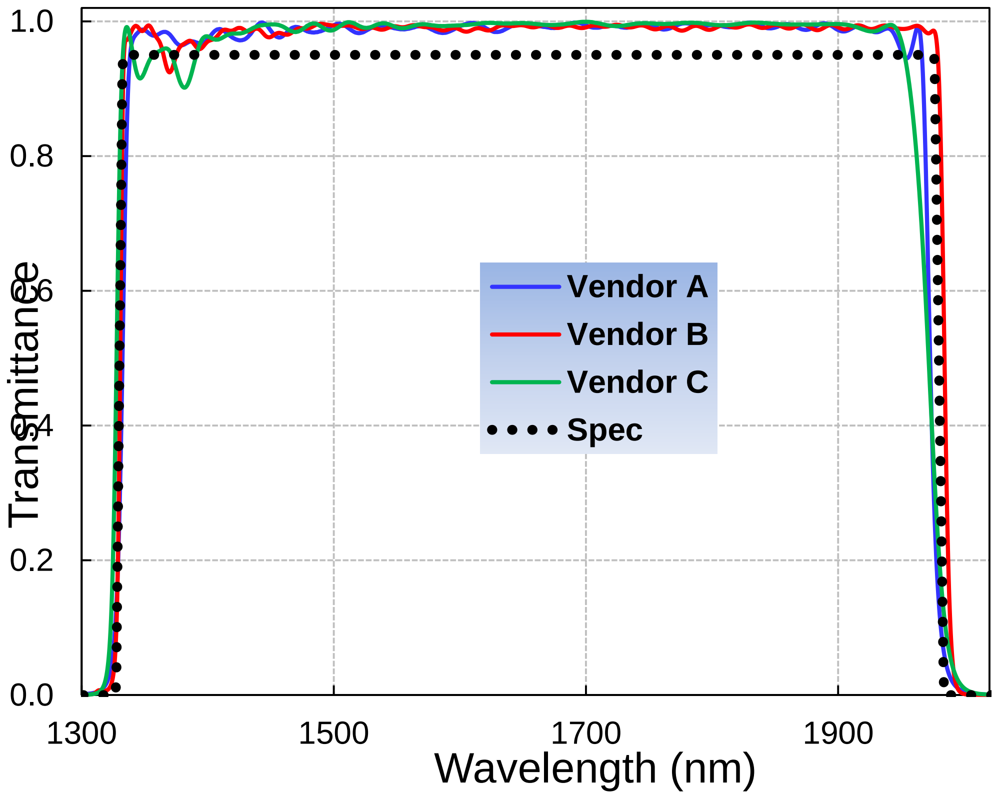


Cryogenic Measurement: Grism

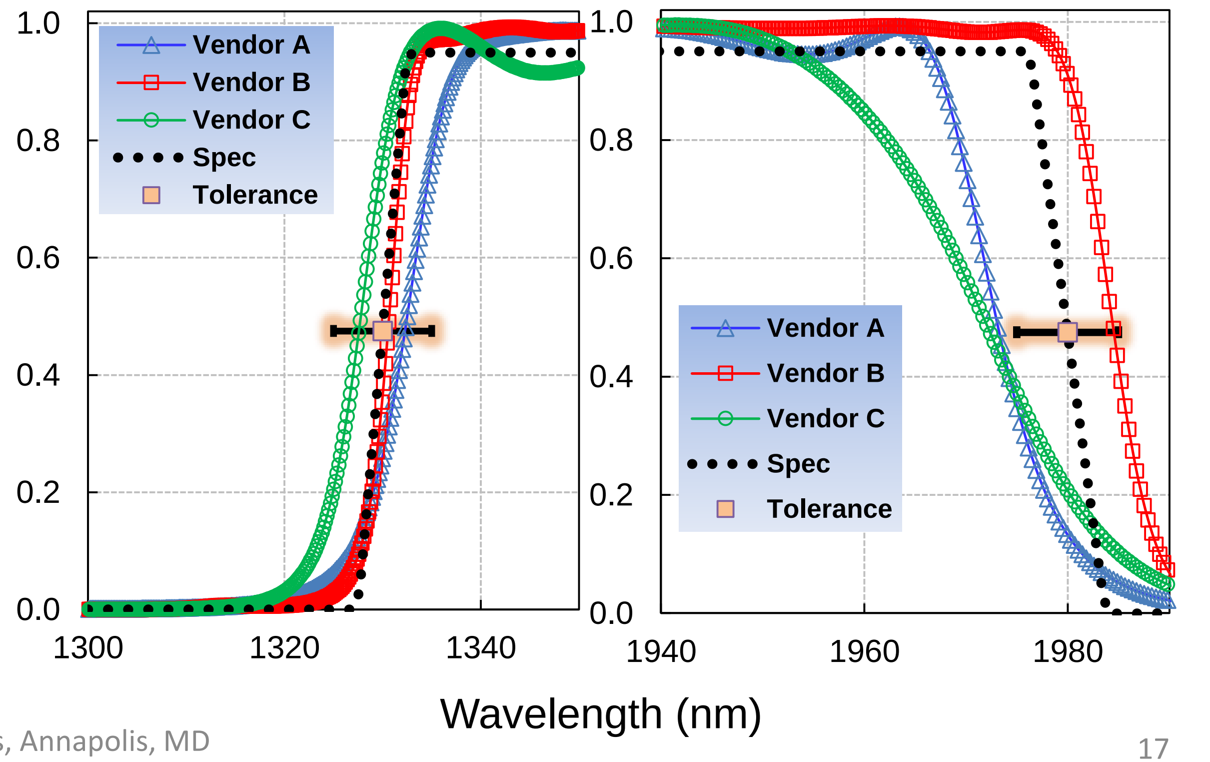
- Comparison among 3 vendors
- Very weak Temperature dependence

- All vendor met the 50% points on the short-side of the pass-band response
- Only one vendor (JDSU) came marginally closed at meeting the long-side slope of the Grism response
- All but one vendor (JDSU) failed the 50% points and the slope requirements on the long-side of the pass-band.
- **We anticipate future flight procurements may be acceptable since the tight slope requirement has been relaxed in recent Cycle6 design .**

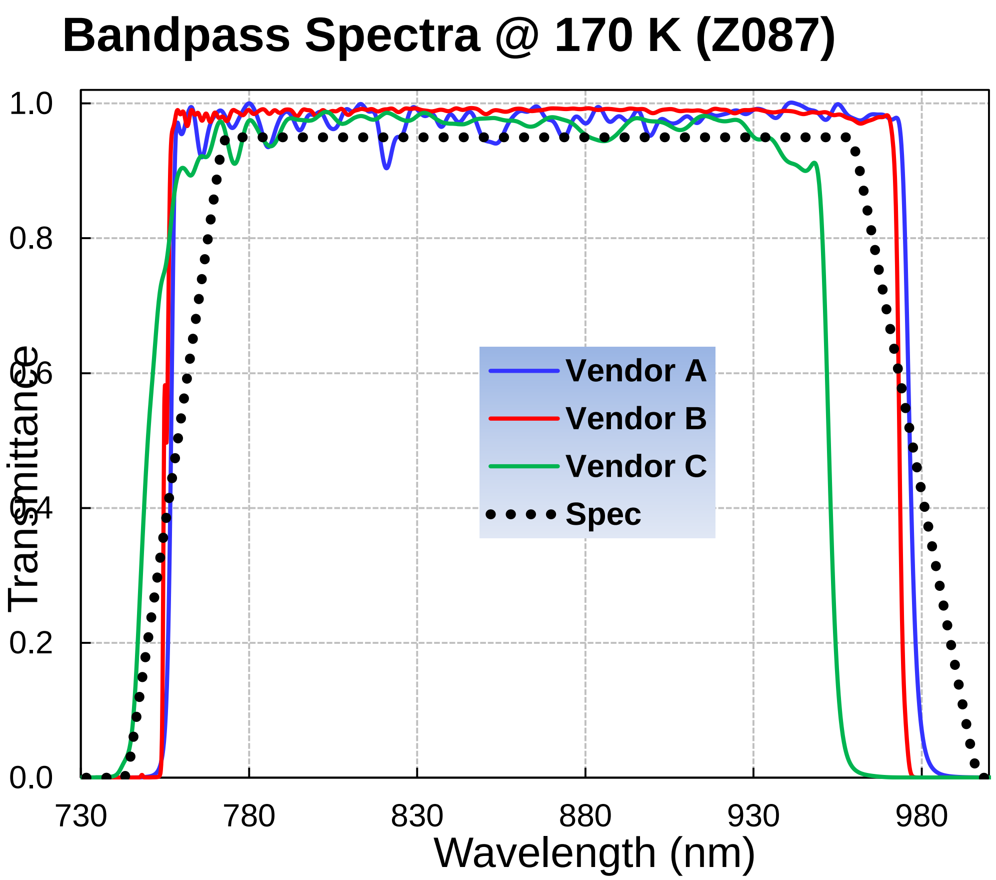
Bandpass Spectra @ 170 K (Grism)



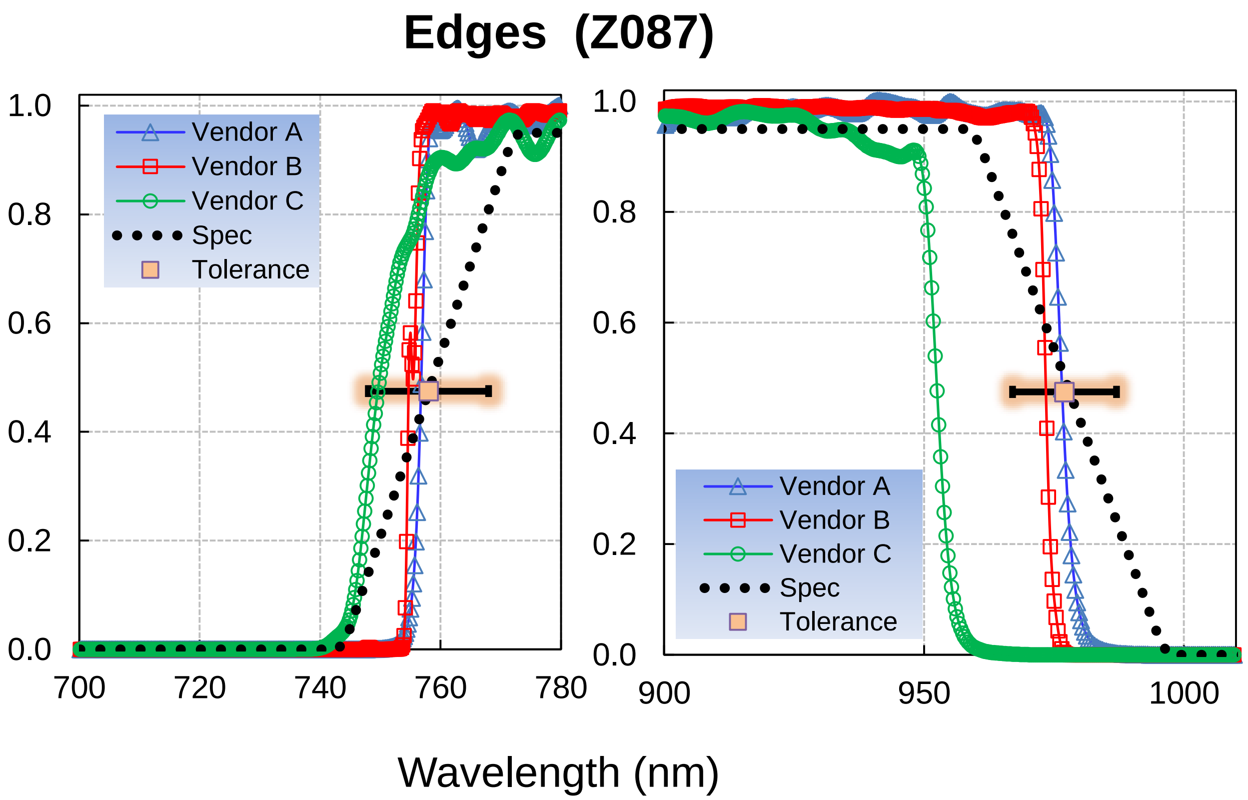
Edges (Grism)



Cryogenic Measurement: Z087



- All vendor met the 50% points on the short-side of the pass-band response
- Two vendors (JDSU and Alluxa) met the 50% points on the long-side.
- All vendors produced slopes that are tighter than the requirements.



Cryogenic Measurement: W149

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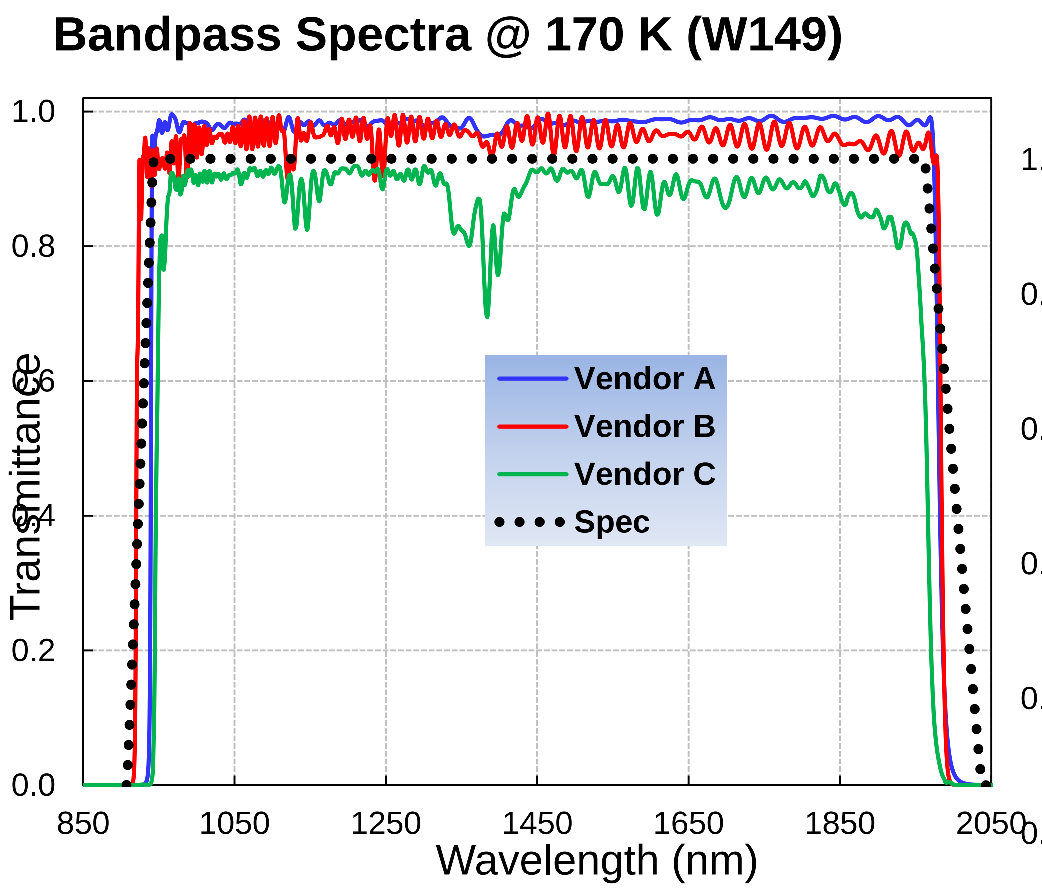
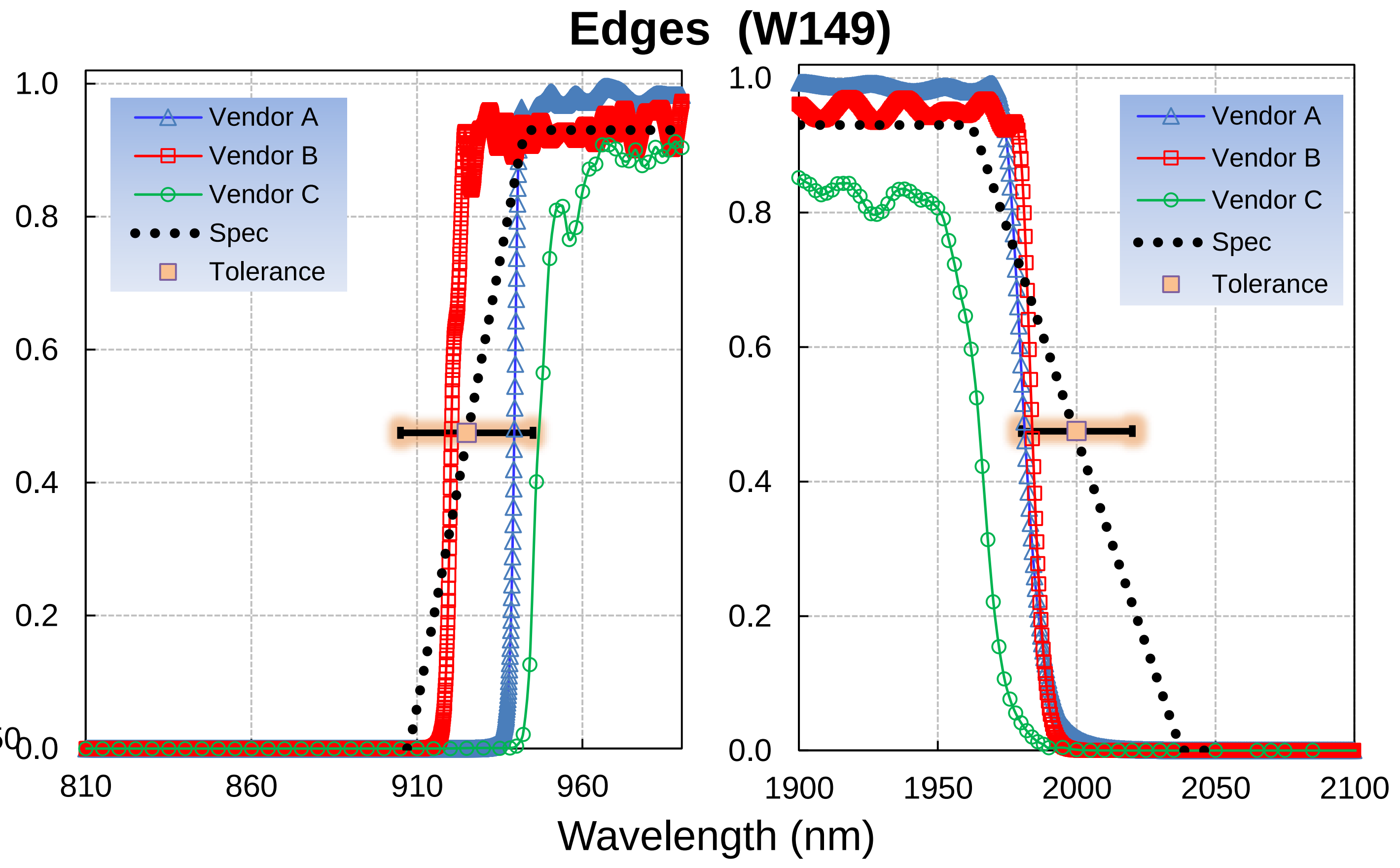




Spectral Performance Summary

- Temp. @ 170 K (Numbers in () @ 295K)
- Numbers in green means vendor met requirements
- Numbers in red means filter failed to meet requirements
- Yellow numbers indicate performance was marginally close at meeting requirements.

Grism	λ_{low} (nm)	λ_{high} (nm)	λ_{center} (nm)	T_{ave} (%)	Slope$_{low}$ (%)	Slope$_{high}$ (%)
Specifications:	1330 ±5	1980 ±5	1655 ±5	≥95	≤0.2	≤0.2
Vendor A	1332 (1333)	1973 (1975)	1652 (1654)	99	0.77	0.70
Vendor B	1331 (1332)	1984 (1986)	1657 (1658)	99	0.40	0.47
Vendor C	1328 (1329)	1972 (1974)	1650 (1652)	99	0.73	1.21

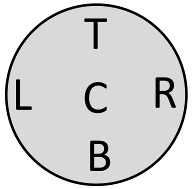
Z087	λ_{low} (nm)	λ_{high} (nm)	λ_{center} (nm)	T_{ave} (%)	Slope$_{low}$ (%)	Slope$_{high}$ (%)
Specifications:	758 ±10	978 ±10	868 ±10	≥95	≤3	≤3
Vendor A	757 (757)	976 (977)	866 (867)	97	0.54	0.58
Vendor B	755 (756)	973 (974)	864 (865)	99	0.51	0.42
Vendor C	750 (750)	952 (953)	851 (852)	95	1.57	0.61

W149	λ_{low} (nm)	λ_{high} (nm)	λ_{center} (nm)	T_{ave} (%)	Slope$_{low}$ (%)	Slope$_{high}$ (%)
Specifications:	925 ±20	2000 ±20	1462 ±20	≥95	≤3	≤3
Vendor A	940 (940)	1981 (1983)	1460 (1462)	98	0.42	0.77
Vendor B	920 (921)	1984 (1985)	1452 (1453)	98	0.93	0.45
Vendor C	945	1965	1456	88	1.15	1.83

Spatial Uniformity: Grism

Chart Legends:

C -> Center
T -> Top
L -> Left
R -> Right
B -> Bottom



- Transmittance of 110mm filter prototypes were measured over a clear (100 mm) aperture
- Spectrometer beam is rectangular (2x10 mm^2)
- Transmittance was checked in a cross pattern across filter clear aperture
- The values in the middle are the wavelengths for the corresponding parameters
- The values at the other locations are the deviations (delta) from the center values
- Variation in bandpass for Grism is < 2.7 nm for all three vendors
- One anomaly for vendor A where the 50% FWHM at λ_{high} is -4.2 nm on Left location.
- Second and 3rd anomalies for vendor C are 50% FWHM at λ_{high} at -9.3 nm and λ_{low} at 6.7 nm on Top locations.

T L C R B	λ_{low} @ 50% T_{ave} (nm)	λ_{high} @ 50% T_{ave} (nm)	T_{ave}
Vendor A	T: -2.1; L: +0.5; C: 1333.5; R: +0.5; B: +1.5	T: +2.5; L: **-4.2**; C: 1973.4; R: +2.6; B: -2.0	T: +0.4; L: -0.2; C: 98.5%; R: +0.3; B: +0.0
Vendor B	T: +1.3; L: 1.1; C: 1325.9; R: +1.4; B: +1.5	T: +2.6; L: +2.4; C: 1974.5; R: +2.7; B: +2.9	T: -0.0; L: +0.2; C: 99.0%; R: +0.1; B: -0.3
Vendor C	T: **+6.7**; L: 0.0; C: 1327.4; R: -0.1; B: +1.5	T: **+9.3**; L: -1.7; C: 1978.1; R: +0.6; B: +2.1	T: +0.1; L: +0.2; C: 98.9%; R: +0.1; B: -1.0

Variation in Bandpass < 3 nm (vendor B)

Spatial Uniformity: W149 & Z087

W149

Position key (circle): T = top, L = left, C = center, R = right, B = bottom

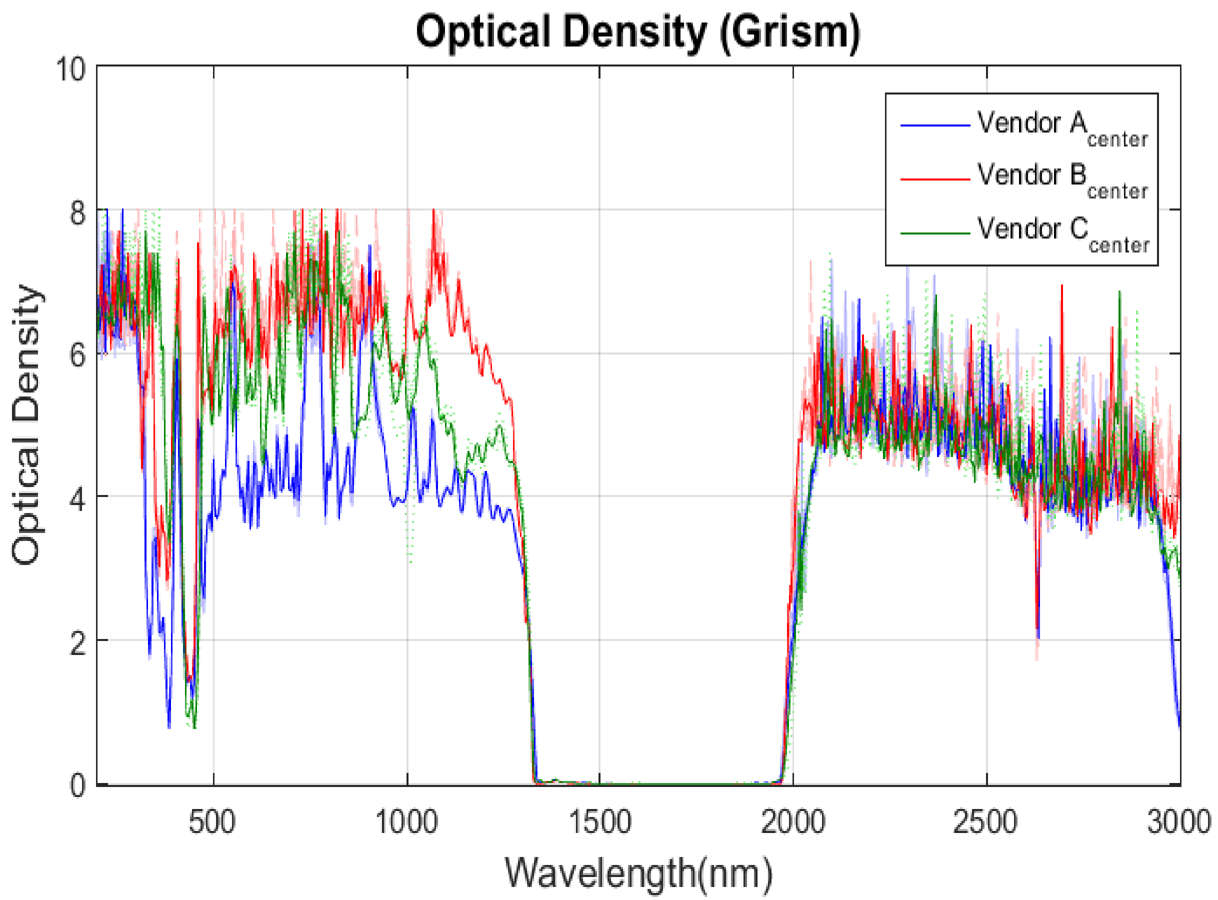
	λ_{low} @ 50% T_{ave} (nm)	λ_{high} @ 50% T_{ave} (nm)	T_{ave}
Vendor A	T +0.5; L +0.6; C 940.7; R +0.1; B **-3.8**	T +1.6; L +1.4; C 1984.6; R +0.2; B -8.2	T +0.1; L +0.0; C 98.9%; R -0.0; B -0.4
Vendor B	T +0.5; L +0.9; C 919.1; R +0.4; B +0.6	T +1.6; L +2.7; C 1977.7; R +1.3; B +2.0	T -0.1; L -0.2; C 96.6%; R -0.2; B +0.0
Vendor C	T +0.2; L -0.0; C 946.5; R -0.1; B +0.1	T +0.5; L +0.5; C 1978.1; R +0.5; B +0.5	T +0.0; L +0.0; C 88.0%; R -1.0; B -0.0

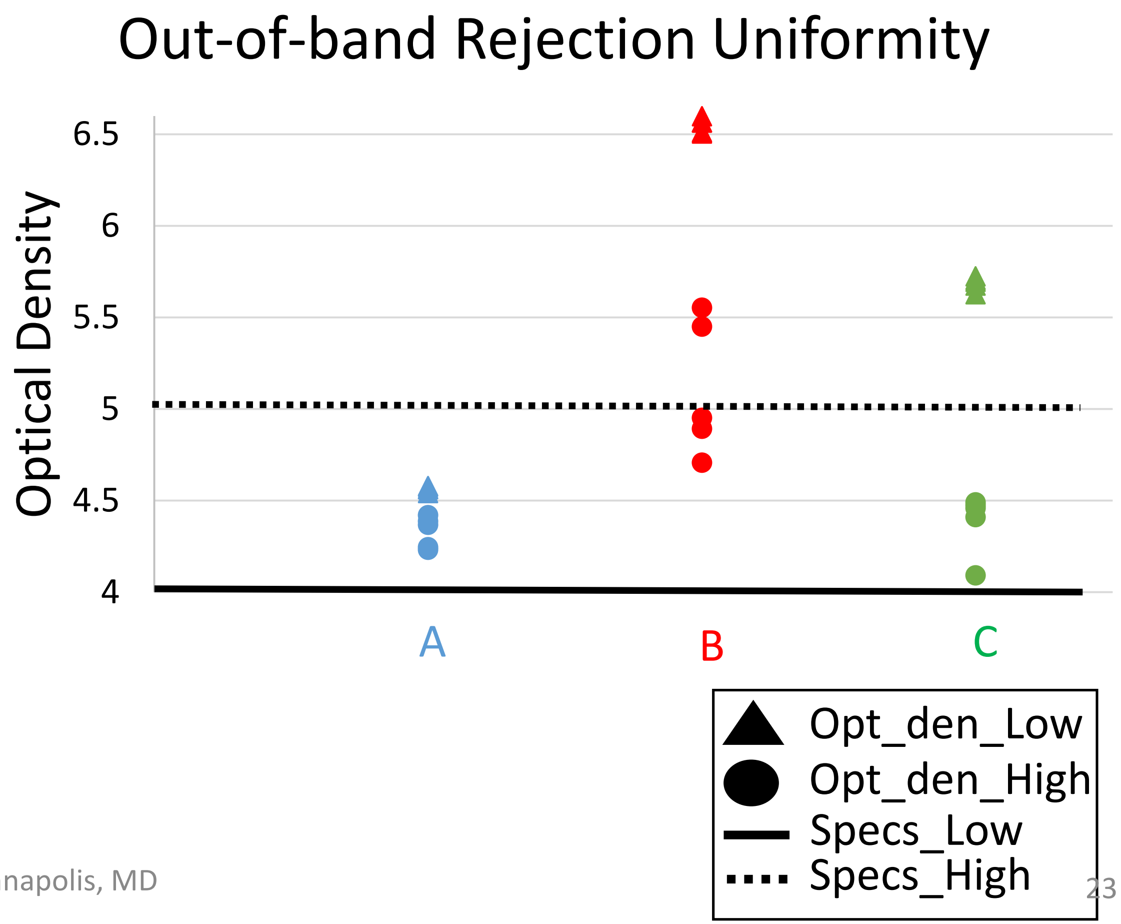
Z087

	λ_{low} @ 50% T_{ave} (nm)	λ_{high} @ 50% T_{ave} (nm)	T_{ave}
Vendor A	T -0.9; L -0.1; C 758.7; R +0.1; B -0.4	T -1.6; L **+8.8**; C 978.4; R +0.3; B +0.2	T -0.2; L -0.0; C 97.4%; R -0.1; B -0.8
Vendor B	T +0.7; L +0.9; C 752.5; R +0.4; B +0.7	T +1.2; L +1.5; C 968.4; R +1.0; B +1.3	T +0.0; L -0.1; C 99.5%; R -0.1; B -0.1
Vendor C	T +0.3; L +0.5; C 753.0; R +0.1; B +0.1	T +1.0; L +0.7; C 954.8; R +0.2; B -0.1	T +0.5; L +0.6; C 94.0%; R +0.4; B +0.0

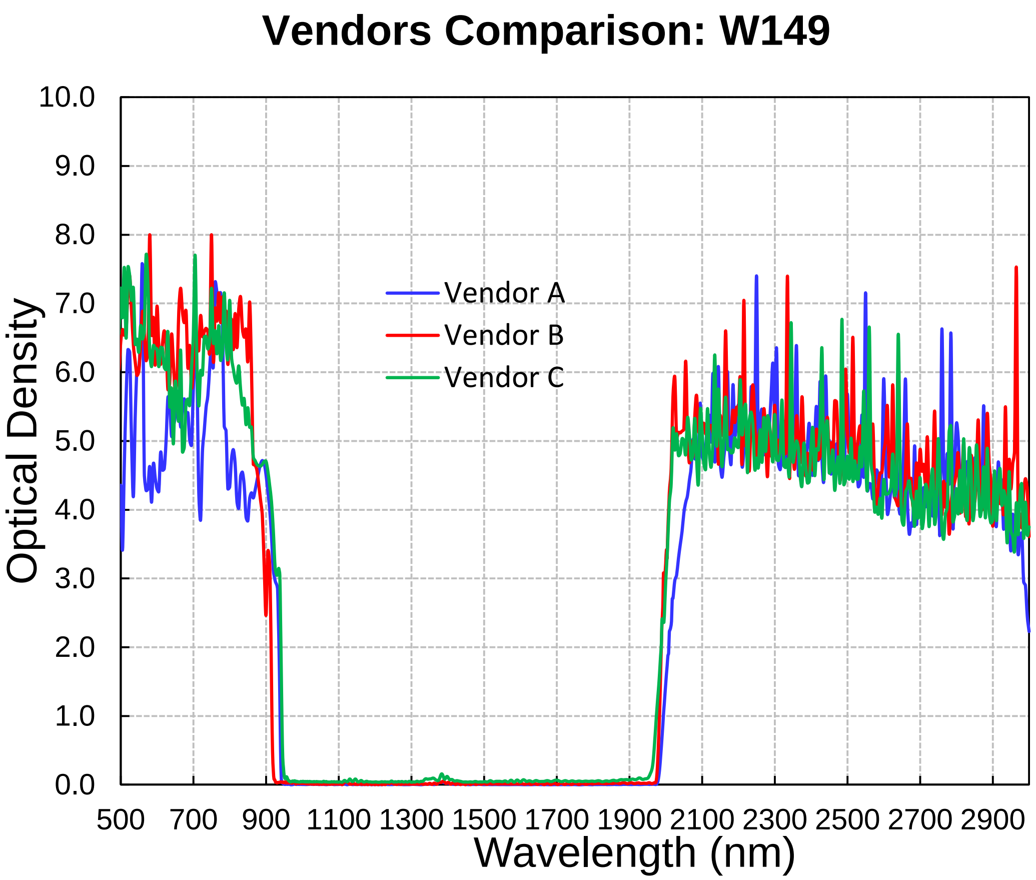
Optical Density: Grism

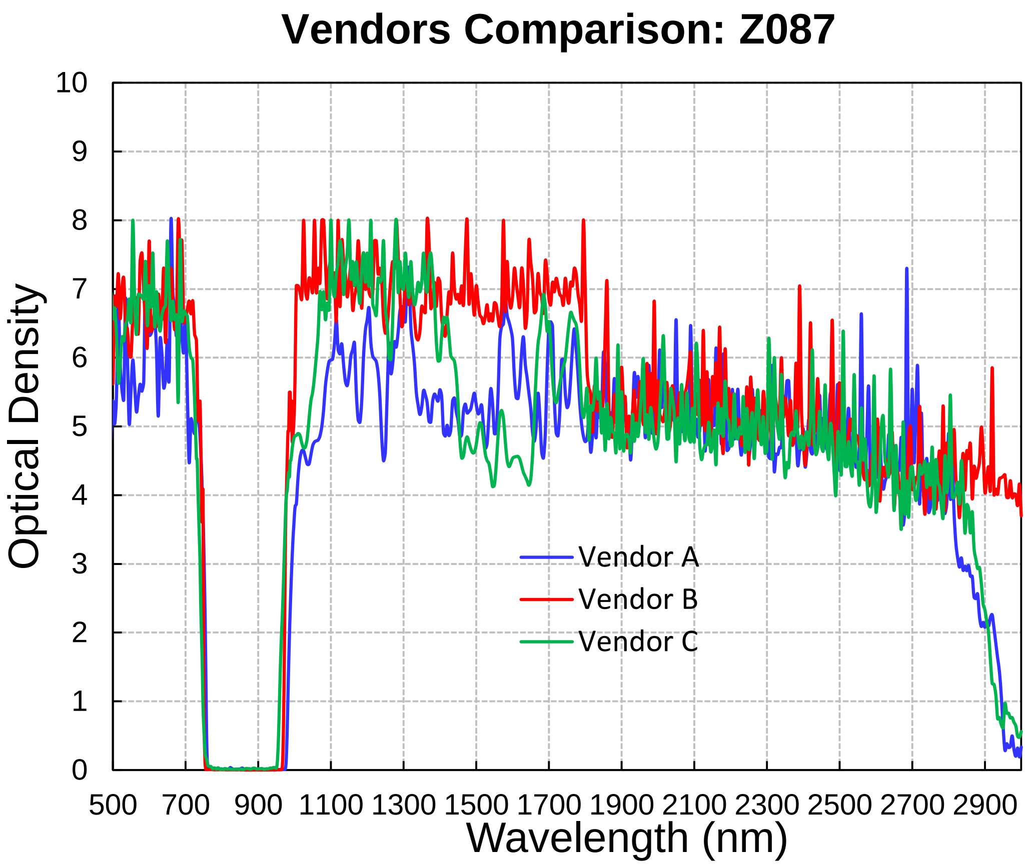
Optical Density = - log10(Transmittance)





Optical Density: W149 & Z087



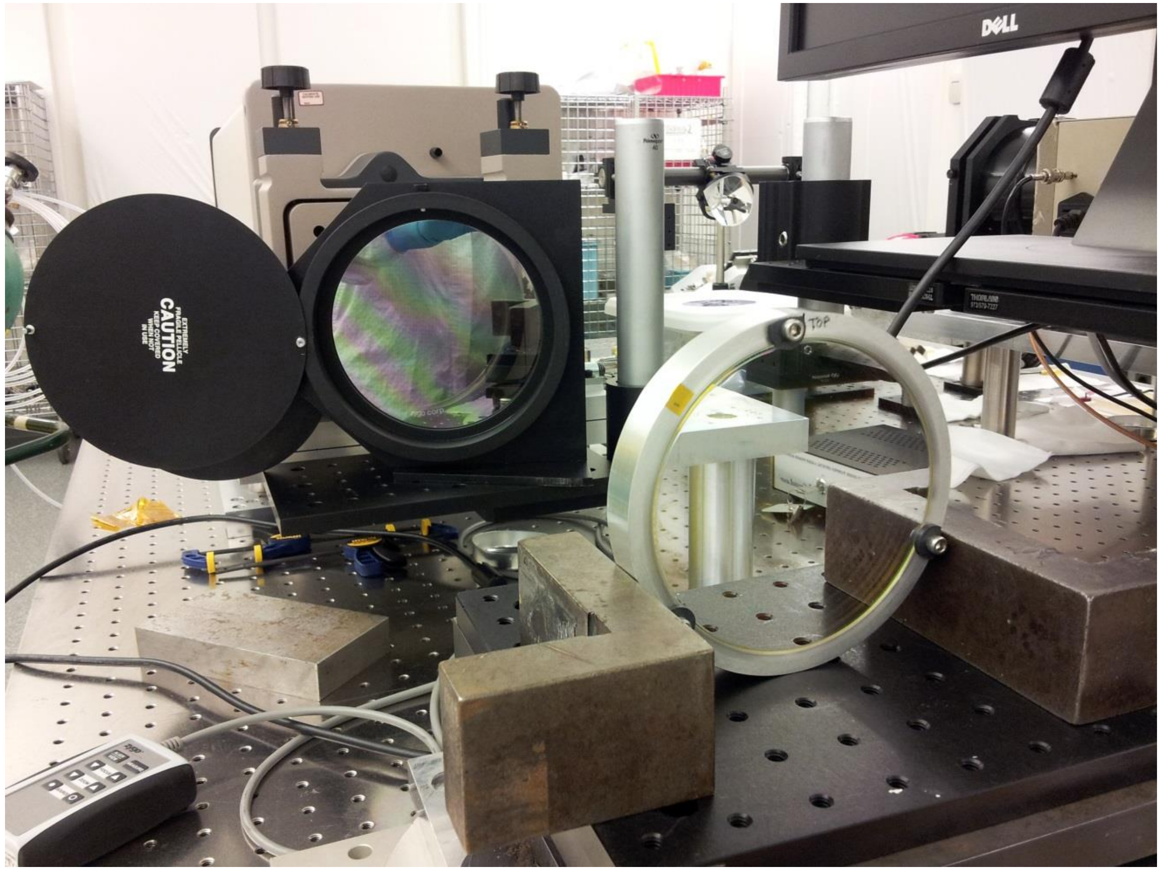


WFE Measurements

Interferometer:
- Zygo Mark-IV

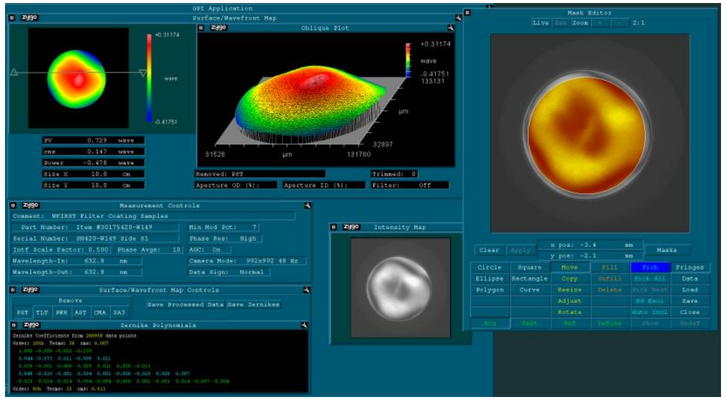
Filter Coating Specifics:
- Fused Silica substrate
- 110mm diameter OD
- 6mm thick

Parts:
- Z087 (SN418-Z087)
  - Item #30175418 Z087 BP Filter V3.2
  - Run #1017-19553-19559
  - Coated 2/20/2015
- GRISM (SN419-GRISM)
  - Item #30175419 GRISM BP Filter V3.2
  - Run #1017-19556-19562
  - Coated 2/23/2015
- W149 (SN420-W149)
  - Item #30175420 W149 WBP Filter V3.2
  - Run #1017-19576-19582
  - Coated 3/4/2015

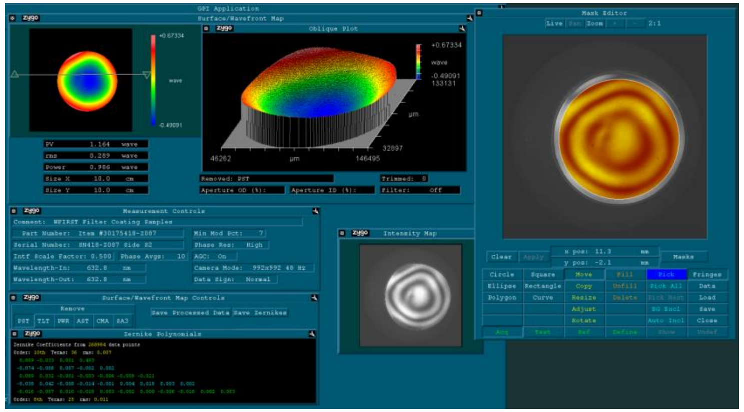


Typical Interferogram

S1



S2



RMS WFE Comparison

Surface Error RMS WFE in ***Waves for λ = 632.8nm***

Filter Type	Surface Side	Vendor A		Vendor B		Vendor C	
		RMS WFE	Power	RMS WFE	Power	RMS WFE	Power
Z087	Side 1	2.931	10.166	0.246	-0.640	1.543	-5.442
	Side 2	2.687	-9.330	0.289	0.986	1.914	6.624
GRISM	Side 1	0.771	-2.751	0.097	-0.191	0.204	0.260
	Side 2	0.719	2.484	0.292	0.928	0.229	0.550
W149	Side 1	1.281	-4.423	0.147	-0.478	N/A	N/A
	Side 2	1.237	4.281	0.069	0.046	N/A	N/A

Compare Surface Error at Ambient & Cryo

Surface Error RMS WFE in ***Waves***
for λ = 632.8nm

Vendor	Ambient at 293K				Cryo at 160K			
	S1 = 'Filter'		S2 = 'Mirror'		S1 = 'Filter'		S2 = 'Mirror'	
	RMS WFE	Power	RMS WFE	Power	RMS WFE	Power	RMS WFE	Power
Z087								
A	2.931	10.166	2.687	-9.330	2.125	-7.316	2.224	7.702
B	0.246	-0.640	0.289	0.986	0.359	-0.970	0.287	0.982
C	1.543	-5.442	1.914	6.624	*2.344*	*-8.070*	2.472	8.538
W149								
A	1.281	-4.423	1.237	4.281	0.876	-3.002	0.662	2.090
B	0.147	-0.478	0.069	0.046	0.316	-0.241	0.074	-0.149
C	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*
GRISM								
A	0.771	-2.751	0.719	2.484	0.592	1.940	0.451	1.554
B	0.097	-0.191	0.292	0.928	0.204	-0.686	0.145	0.332
C	0.204	0.260	0.229	0.550	0.512	1.766	0.656	-2.240

Conclusions

- Spectral characterization of band-pass filters subset WFIRST/AFTA WFI imager. Most filters met parameters, such as the in-band transmission rates, out-of-band rejections, and sharpness of the edges.

- The position of band-pass transmission curve is very weakly temperature-dependent. It shifts towards the low-wavelength region as temperature decreases.

- The RMS WFE distortion was an order of magnitude smaller for vendor B *versus Vendor A*

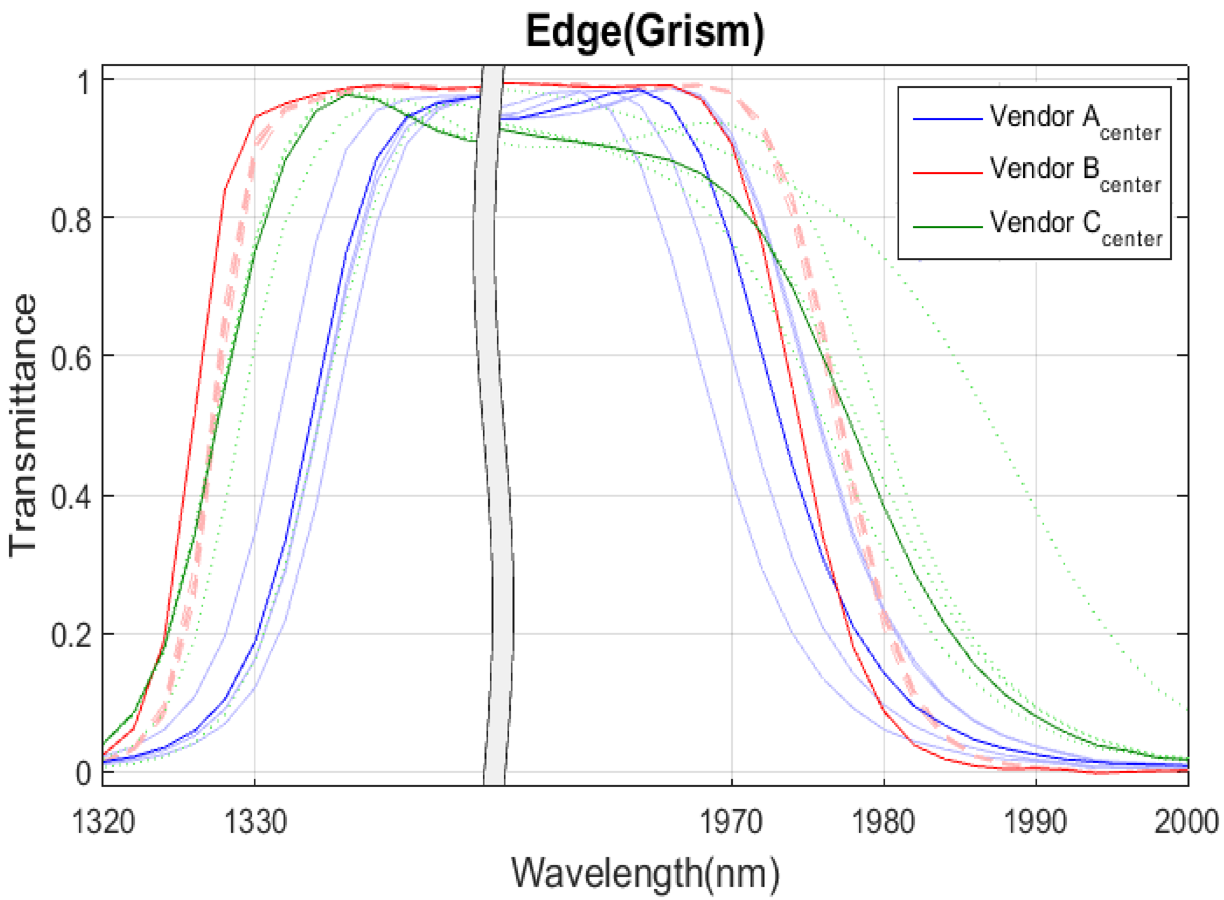
WFE System Impact

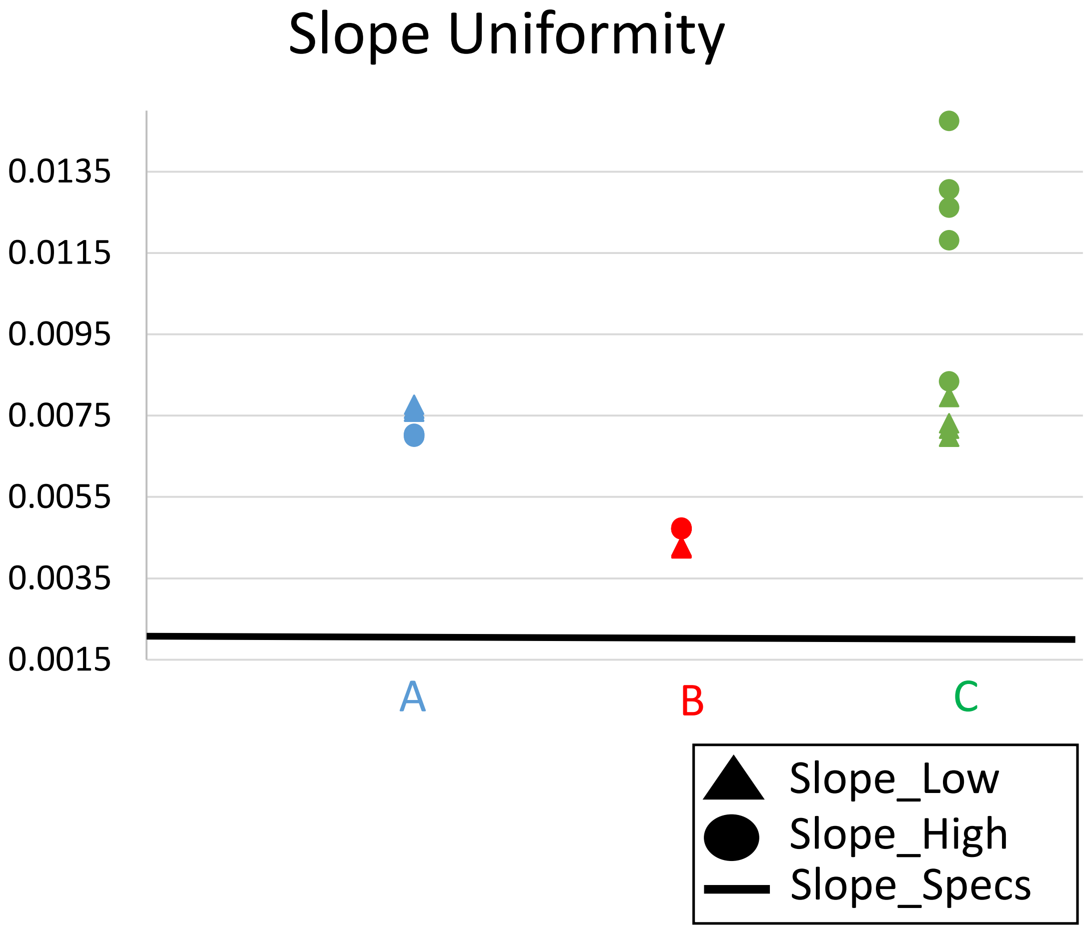
The Fringe Zernike files were imported into Code V
WFE performance was compared to nominal design residual
Change in Fold Mirror (F2) Position for WFE Compensation
Resulting Change in System WFE = Δ RMS WFE

WIM System Impact in ***Microns*** *for Δ's RMS WFE & F2 Position*

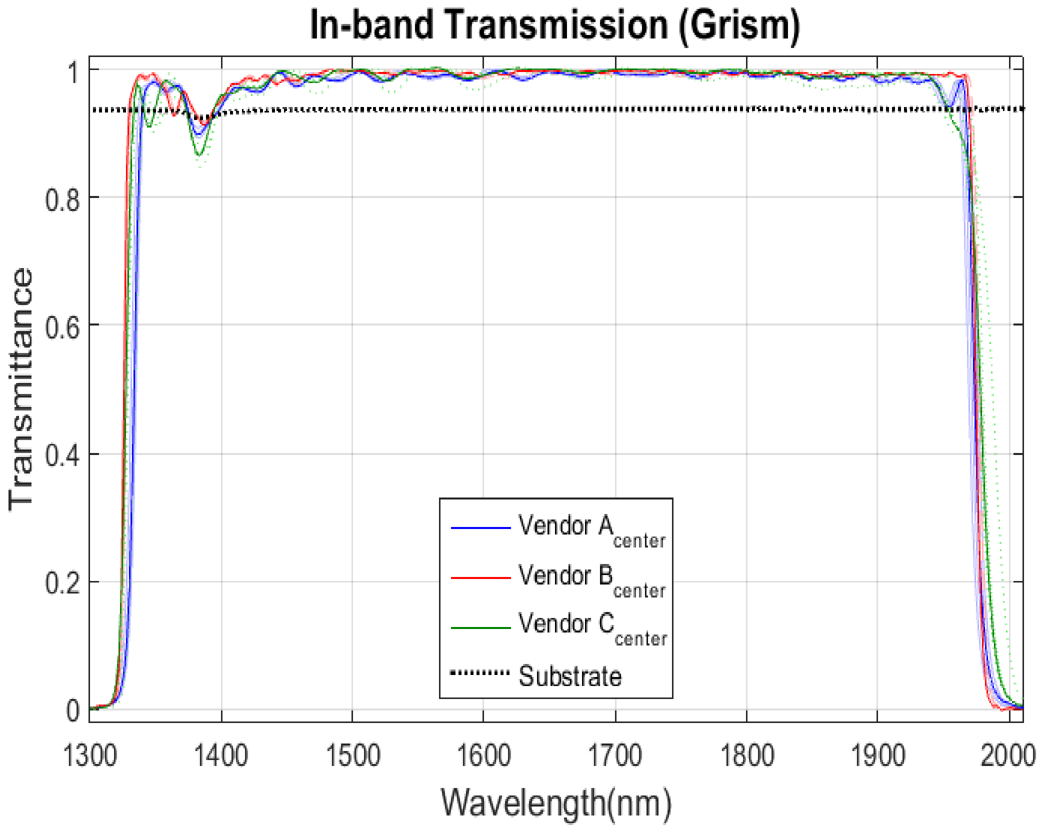
Coating Name	Uncoated			Vendor B			Vendor A		
	Δ RMS WFE	Δ F2 Position	Ratio S1/S2 Power	Δ RMS WFE	Δ F2 Position	Ratio S1/S2 Power	Δ RMS WFE	Δ F2 Position	Ratio S1/S2 Power
Uncoated	0.004	34	0.474						
Z087				0.002	13	0.649	0.007	35	1.090
GRISM				0	33	0.206	0.007	-12	1.107
W149				0.002	-19	10.391	0.001	-5	1.033

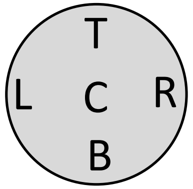
Spatial Uniformity





Grism In-Band Spatial Uniformity





λ_L _0.5T (nm)	λ_H _0.5T (nm)	T_IB
T: -2.1, L: +0.5, C: 1333.5, R: +0.5, B: +1.5	T: +2.5, L: -4.2, C: 1973.4, R: +2.6, B: -2.0	T: +0.4, L: -0.2, C: 98.5%, R: +0.3, B: +0.0
T: +1.3, L: +1.1, C: 1325.9, R: +1.4, B: +1.5	T: +2.6, L: +2.4, C: 1974.5, R: +2.7, B: +2.9	T: -0.0, L: +0.2, C: 99.0%, R: +0.1, B: -0.3
T: +6.7, L: -0.0, C: 1327.4, R: -0.1, B: +1.5	T: +9.3, L: -1.7, C: 1978.1, R: +0.6, B: +2.1	T: +0.1, L: +0.2, C: 98.9%, R: +0.1, B: -1.0

(1) Most sample filters meet the proposed specifications. Optical properties, such as the in-band transmission rates, out-of band rejections, and sharpness of the edges, will be considered by the WFIRST design for further vendor selection.

(2) The position of band-pass transmission curve is temperature-dependent. It shifts towards the low-wavelength region as temperature decreases.