Spectral and Wavefront Error Performance of WFIRST/AFTA Prototype Filters

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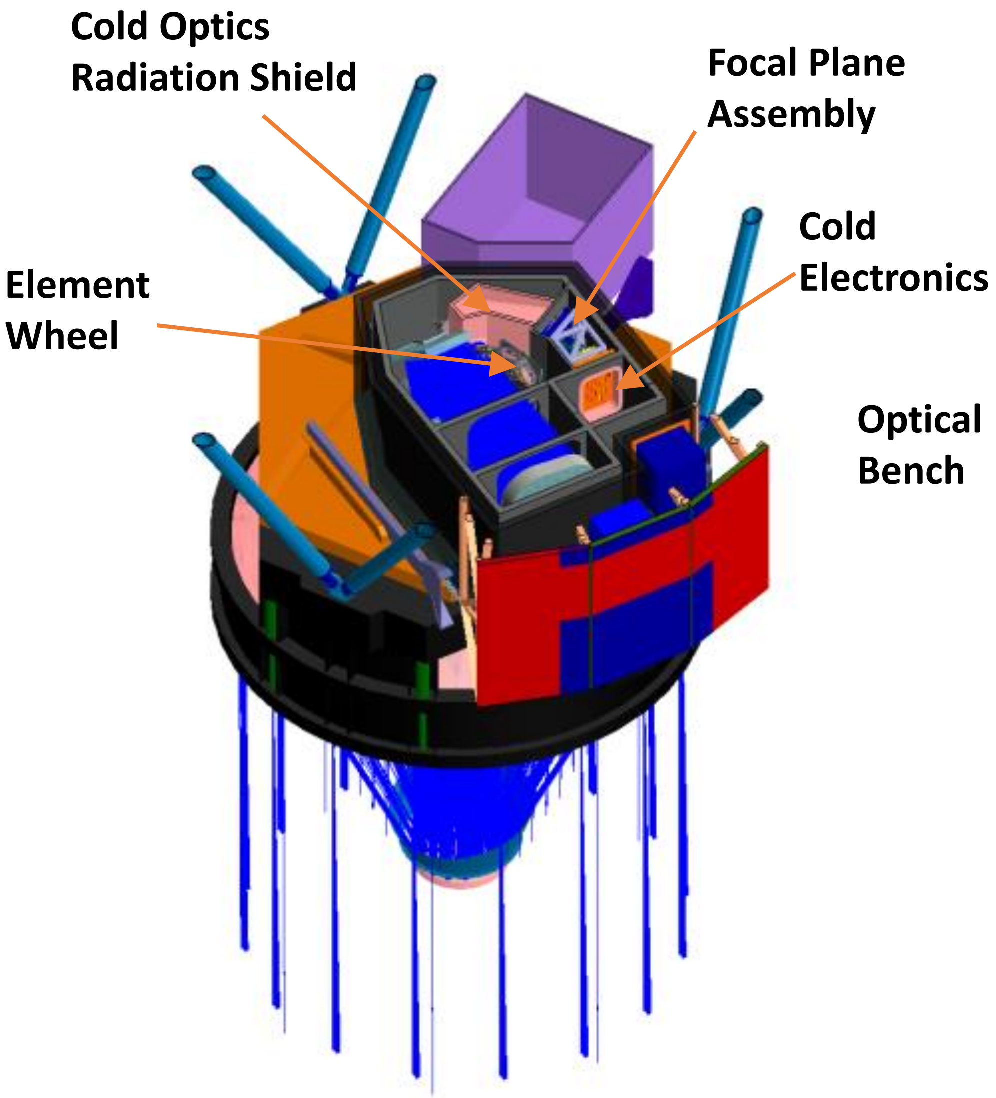
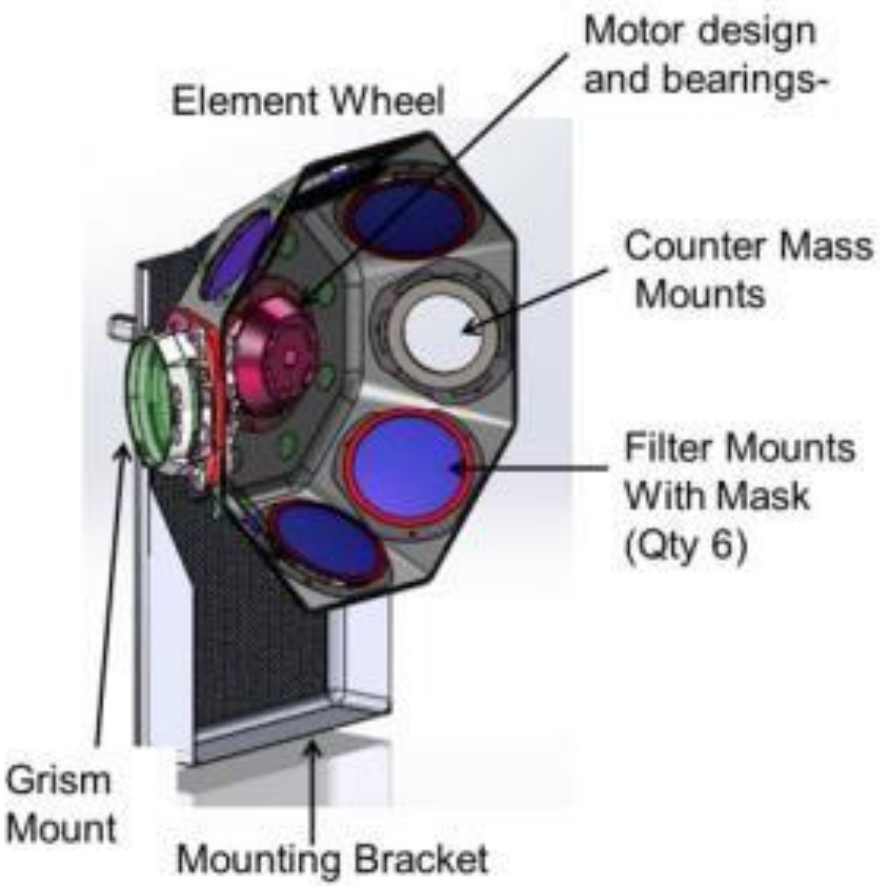
Wide Field Instrument Overview

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

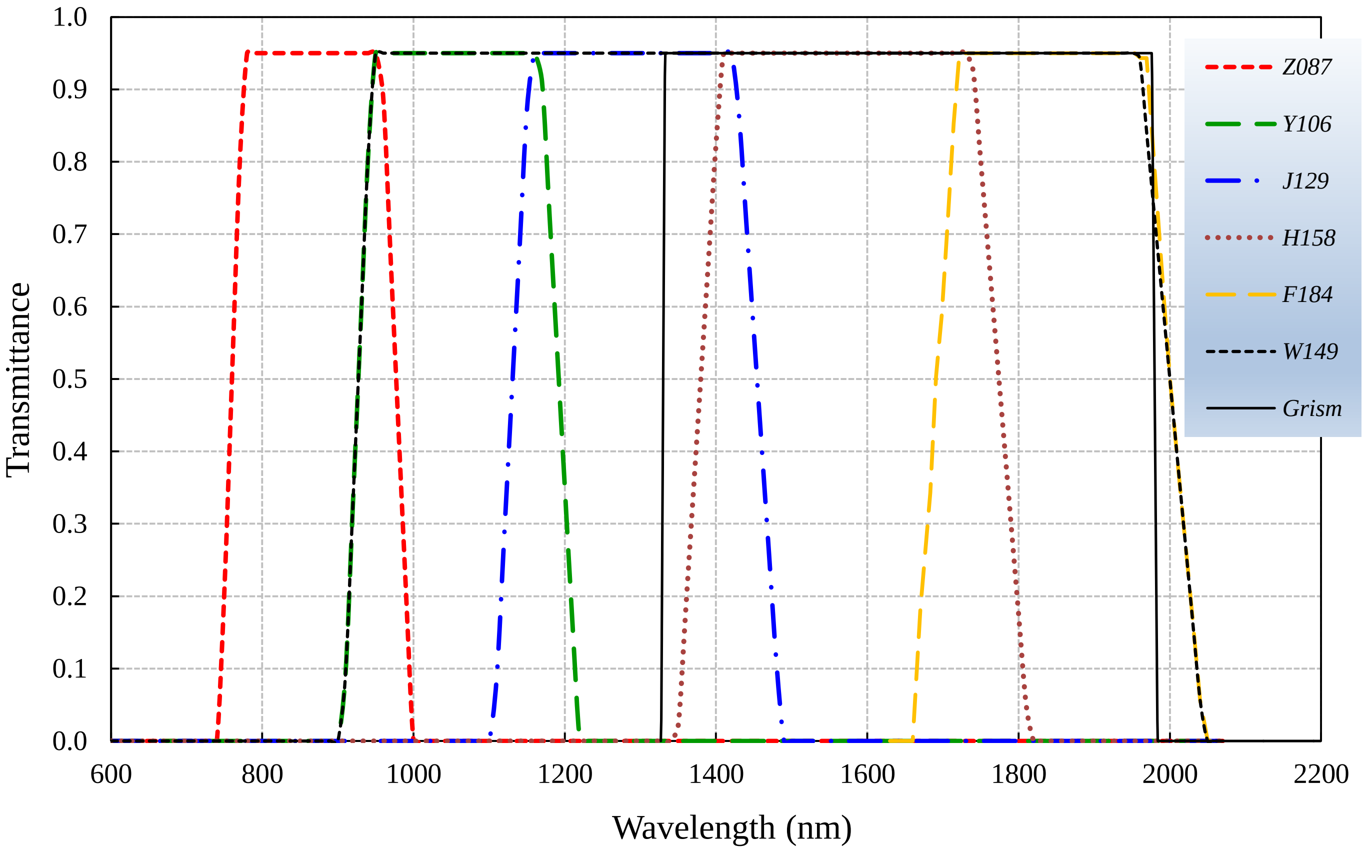
#	Min (mm)	Max (mm)	R	SN Detect Shallow	SN Detect Med/Deep	SN Spec	HLS Image	HLS Spec	Microlensing Monitor	Microlensing Color	Avail for GO
Z087	0.760	0.977	4.0							2X daily	
Y106	0.927	1.192	4.0	X			Photo-z				
J129	1.131	1.454	4.0	X	X						
H158	1.380	1.774	4.0		X		Photo-z & Shapes				
F184	1.683	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 Performance

- Stability of the bandpass over time
- For the grism, the edges of the bandpass need to be sharp. If we have to prioritize one edge, the blue edge will have higher priority
- The imaging bands must overlap some
- Throughput
- Uniformity
- Trade between sharpness of edge and ringing is TBD for the imaging filters
- Specific values of cutoff wavelength

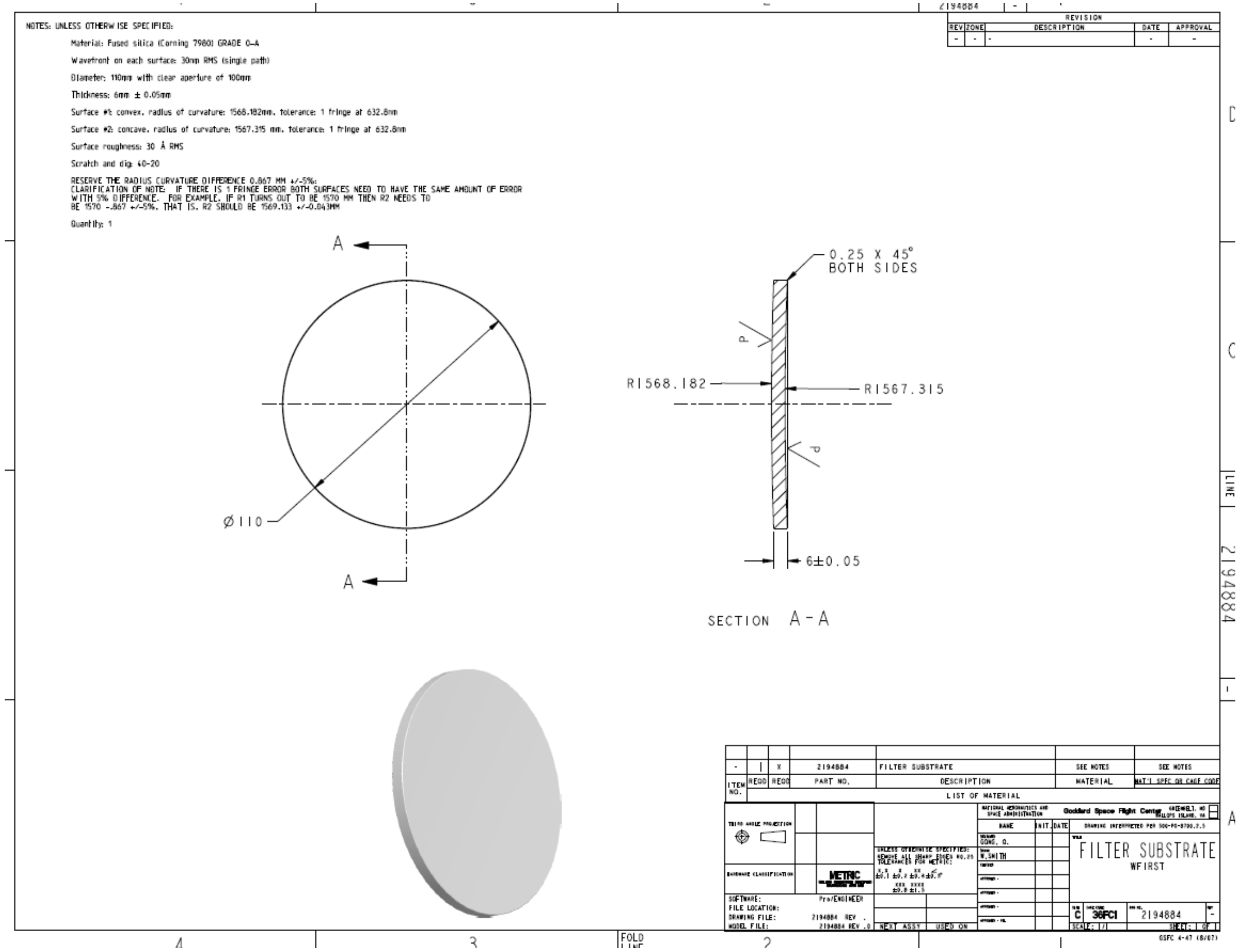


Objectives

- Procurement of a subset WFI filter complement (Grism, W149, and Z087) from 3 different vendors
- 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

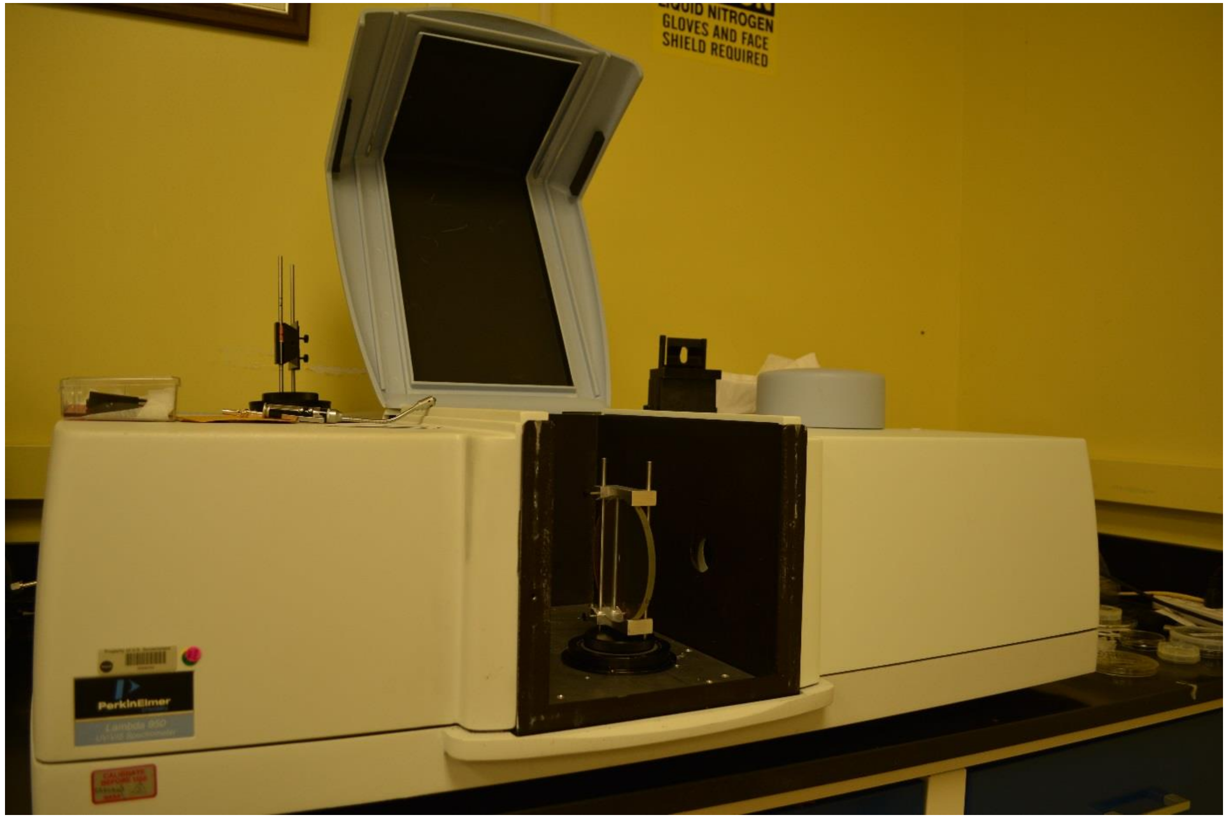
- Flat substrate disks (110 mm x 6mm, Corning 7980).
- Reflected WFE performance (<0.5 wave PV @ 632.8 nm).
- 20/10 scratch/dig
- Substrates were sent to 3 vendors (3 EA) for bandpass coating application.
- One inch coupons were also requested (for cryogenic measurement purposes)
- **The selected coating vendors are:**
  - **Vendor A**
  - **Vendor B**
  - **Vendor C**



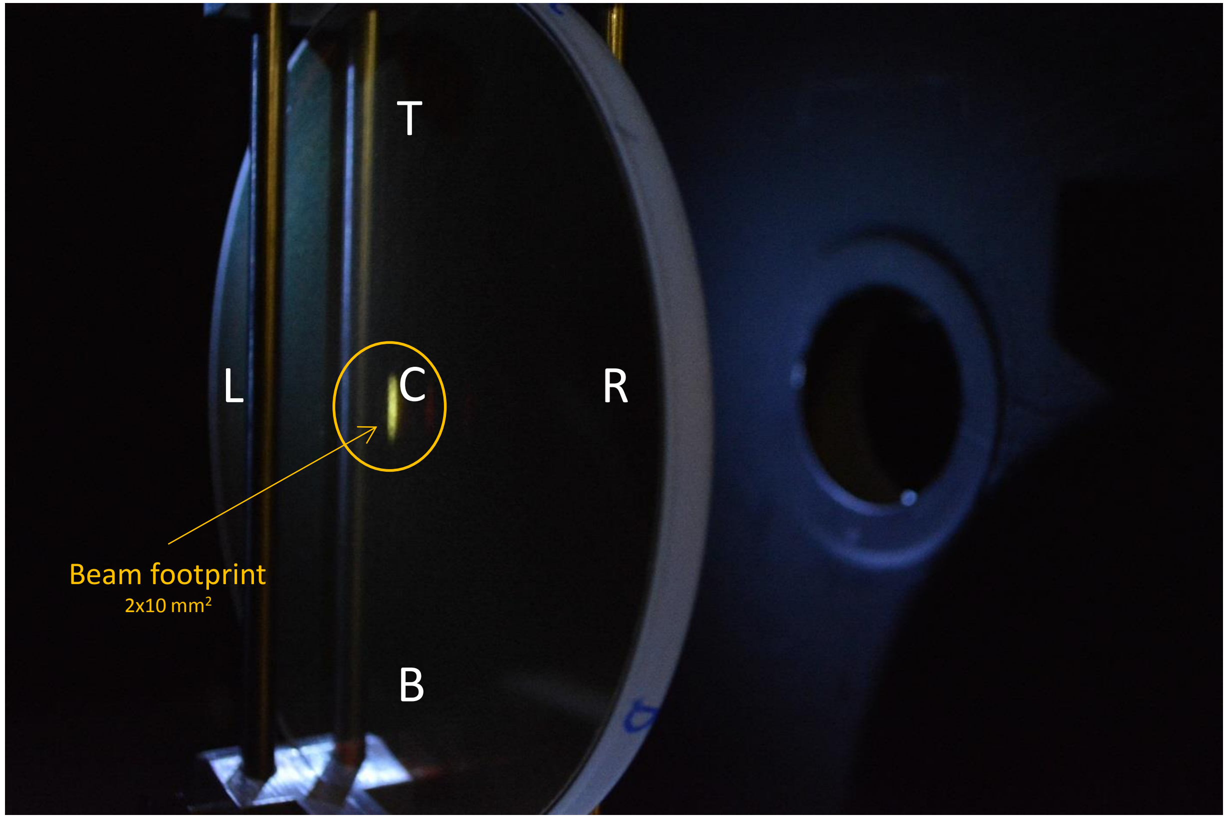
Spectral Characterization

Perkin Elmer Spectrometer (950)

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



Spectral uniformity



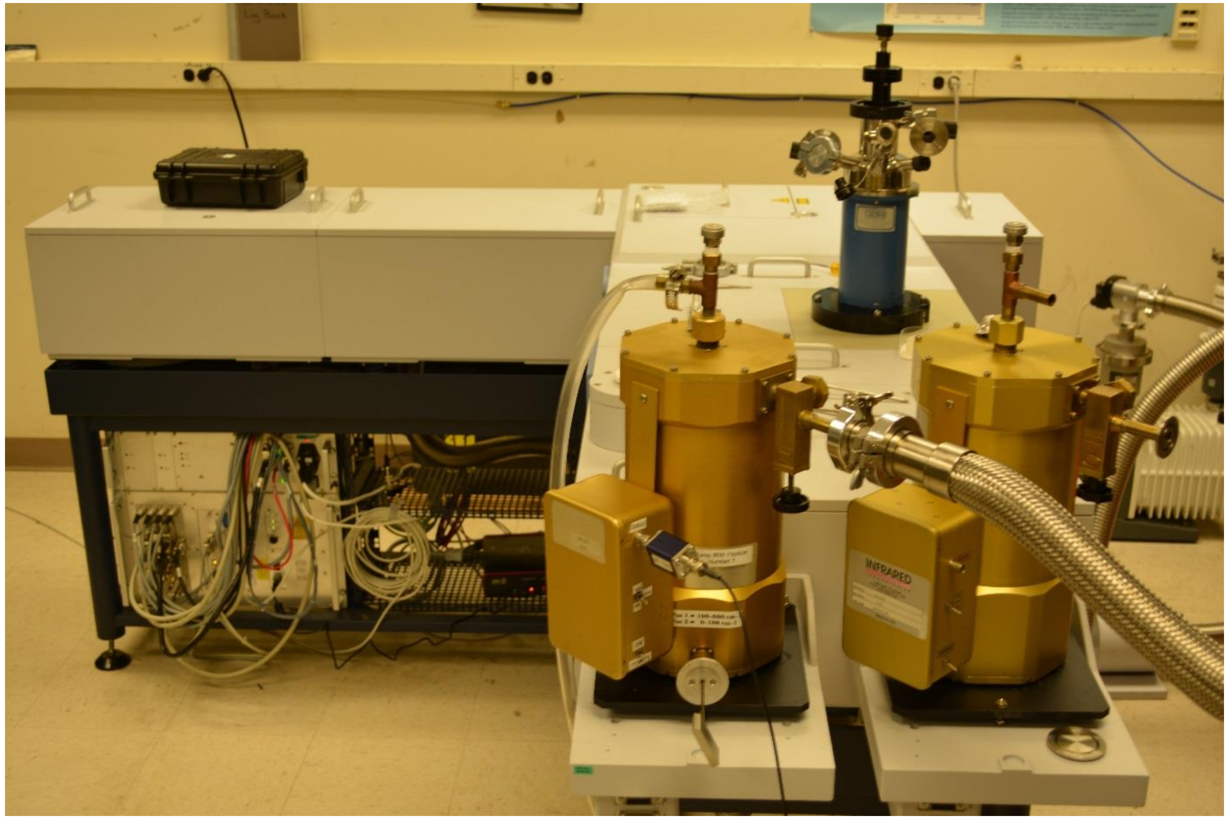
Cryogenic Measurements

Bruker Spectrometer

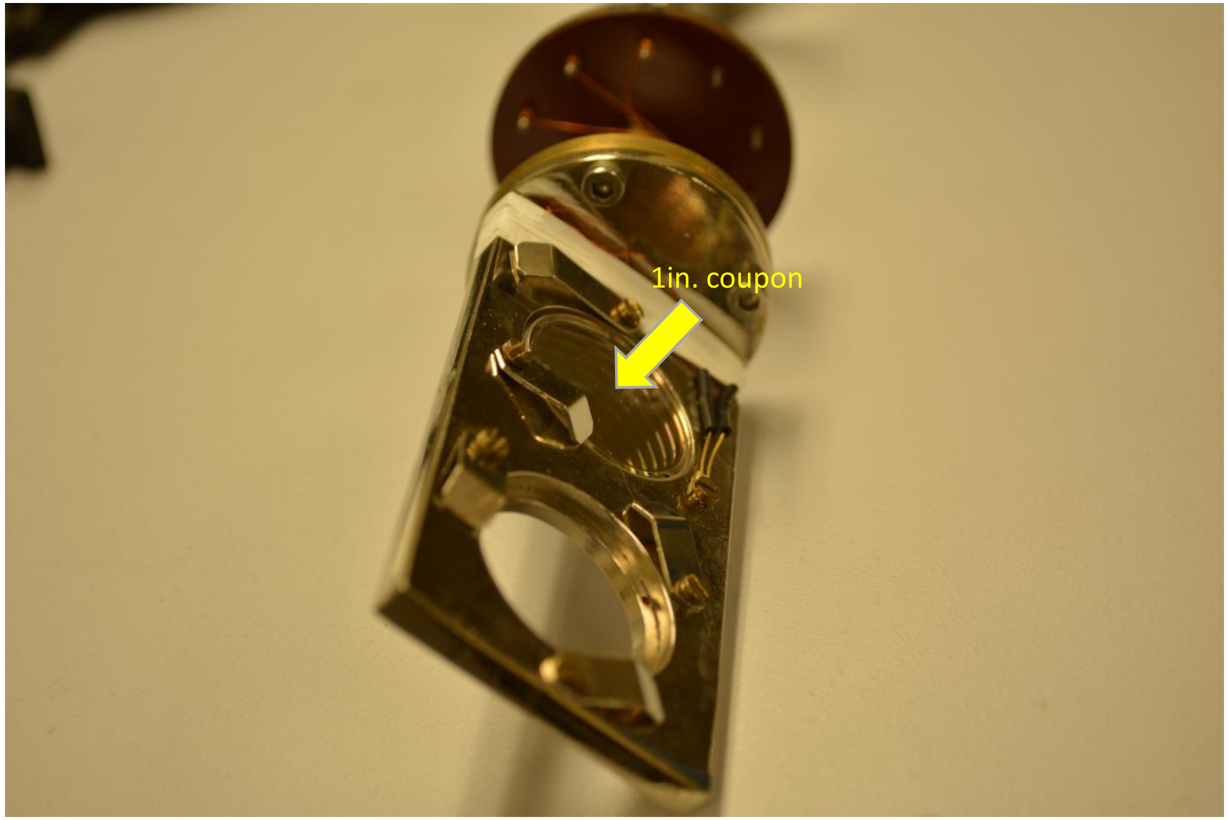
Fourier Transform Spectrometer (FTS)

1000-10000 nm (Res. < 0.05 nm)

Photometric accuracy (3-4A)

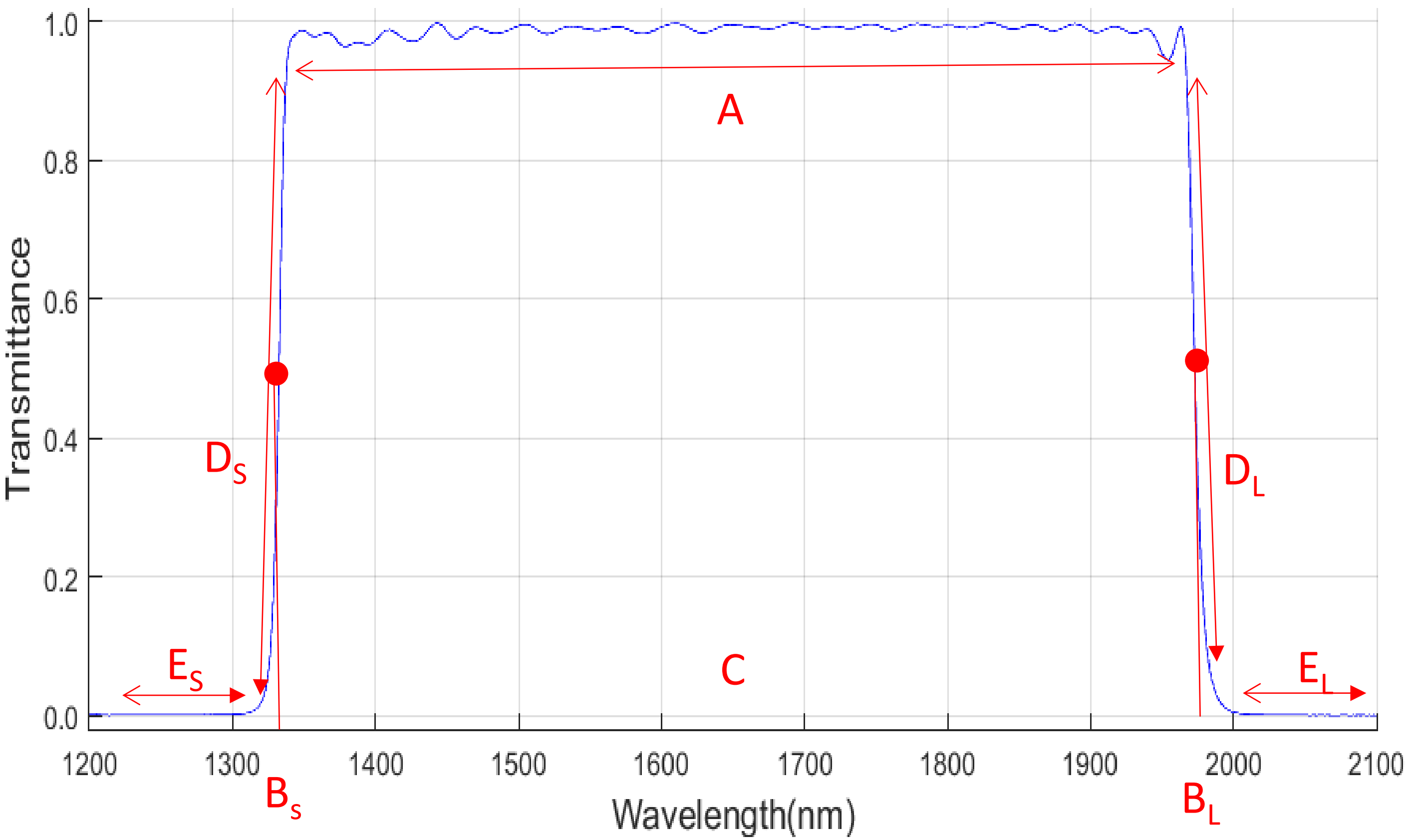


Cryostat Sample holder



Band-Pass Parameters

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



A : Ave. In-band Transmission (T_{AVE})

B : Wavelengths @ 50%T_{AVE}

- B_s: Short Side
- B_L: Long Side

C : Center Wavelength (λ_C)

$$\lambda_C = (\lambda_{@50\%T_{AVE}} + \lambda_{@50\%T_{AVE}})/2$$

D : Slope Edges

- D_S: Short Side
- D_L: Long Side

$$\text{Slope} = |\lambda_{@90\%T_{AVE}} - \lambda_{@10\%T_{AVE}}| / \lambda_{@50\%T_{AVE}}$$

E : Ave. Out-of-band optical density

- E_S: Short Side
- E_L: Long Side

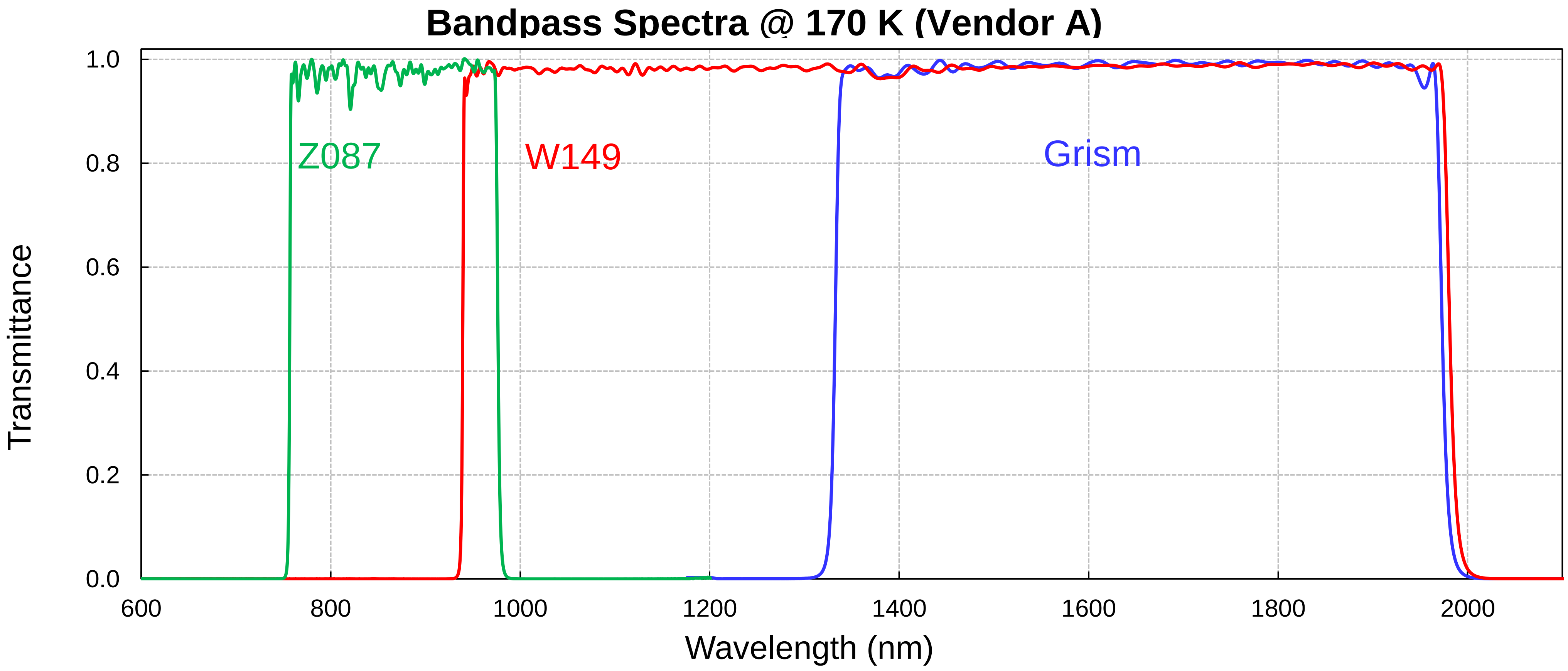
$$\text{Opt\_Den} = -\log10(\text{Transmittance})$$

Band-Pass Parameters Cont…

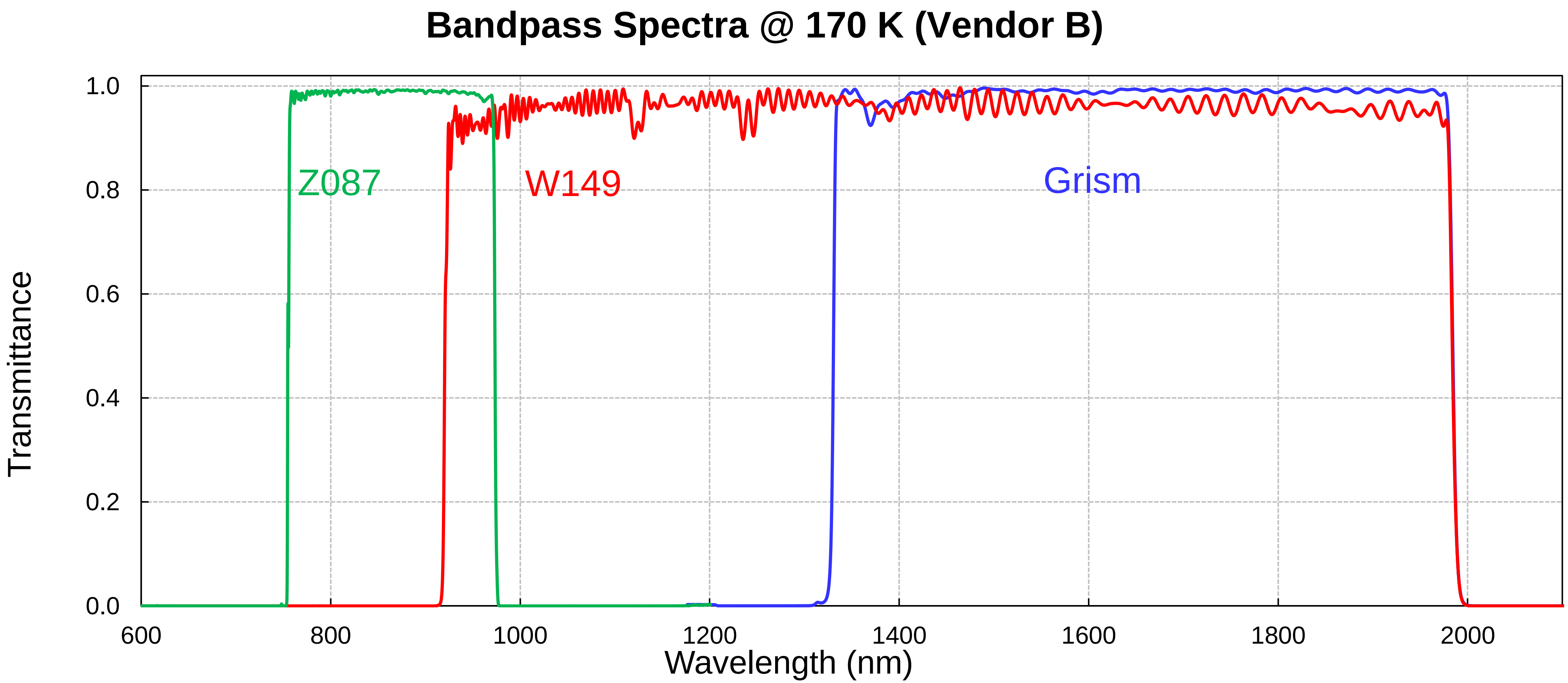
	BANDPASS REQUIREMENTS (Cycle5)		
Parameter	Grism	Z087	W149
A	$\geq$ 95%	$\geq$ 95%	$\geq$ 93%
B_s	1345 nm (±5 nm)	758 nm (±10 nm)	925 nm (±20 nm)
B_L	1955 nm (±5 nm)	978 nm (±10 nm)	2000 nm (±20 nm)
C	1650 nm (±5 nm)	868 nm (±10 nm)	1462 nm (±20 nm)
D_s, D_L	$\leq$ 0.2%	$\leq$ 3%	$\leq$ 3%
E_s	OD 4 (500-1250 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: Alluxa Inc.

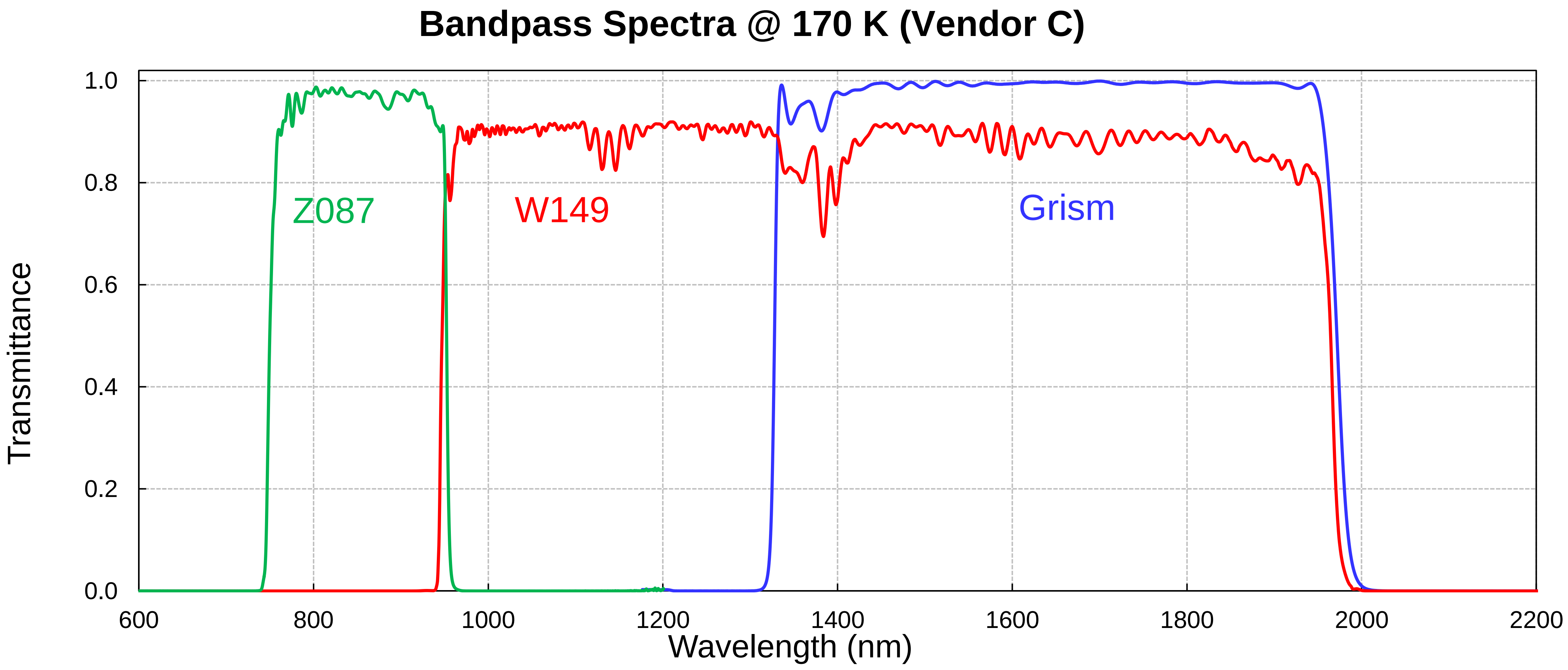
Spectral performance for Grism, W149, and Z087 filter prototypes (25 mm coupons)



Spectrum Overview: Vendor B



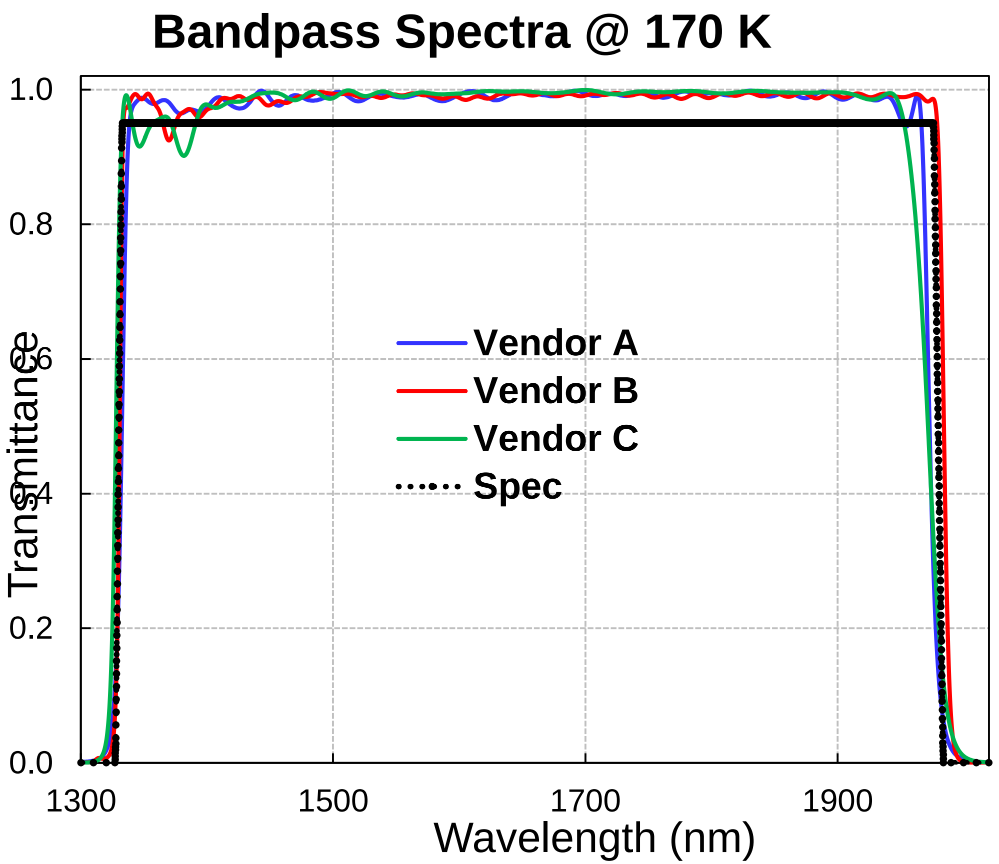
Spectrum Overview: Vendor C

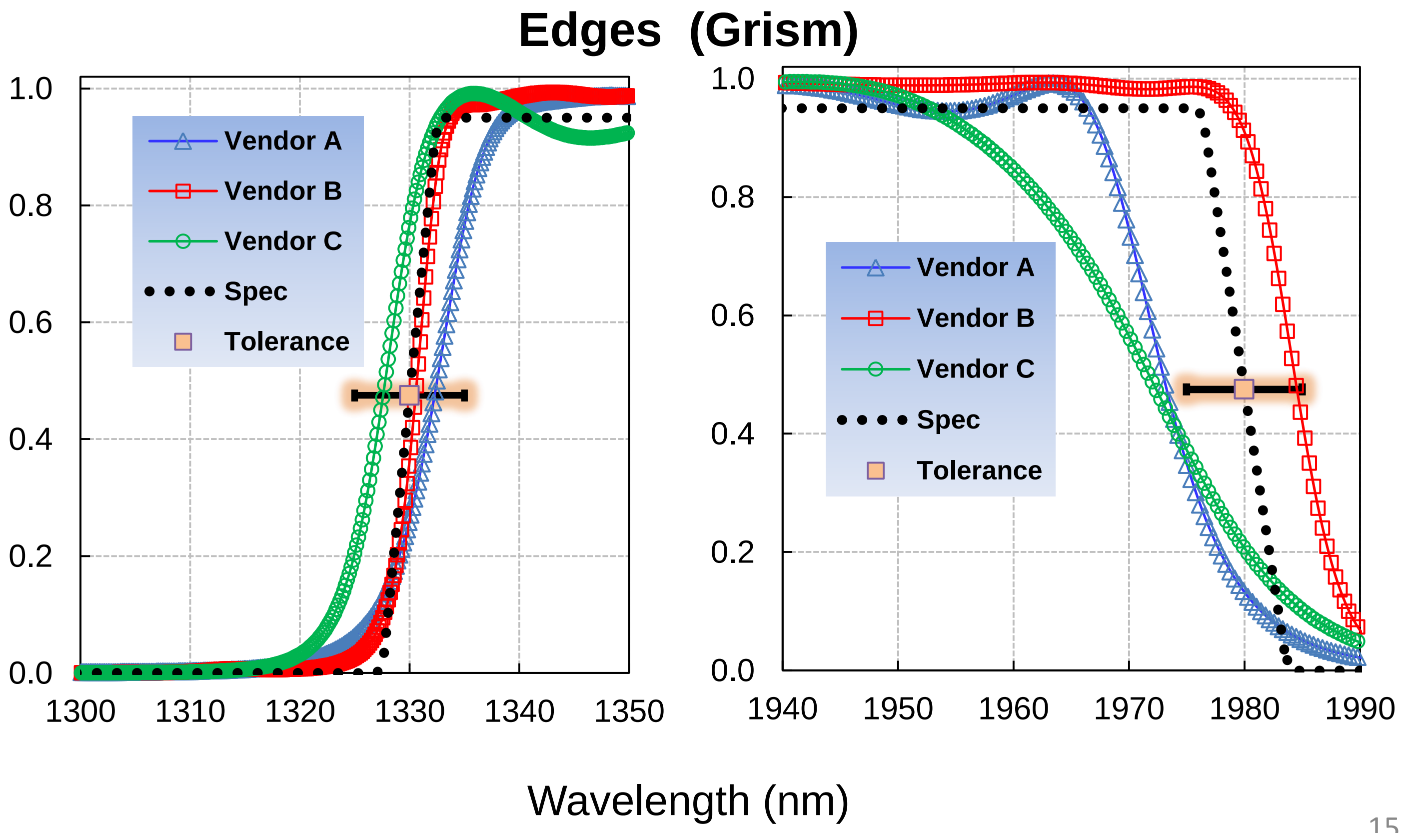


Vendor Comparison: Grism

- Comparison of Grim filter responses among 3 vendor.

- All vendor met the 50% points on the short-side of the pass-band response
- Only one vendor (Vendor B) came marginally closed at meeting the long-side slope of the Grism response
- All but one vendor (Vendor B) 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 .**

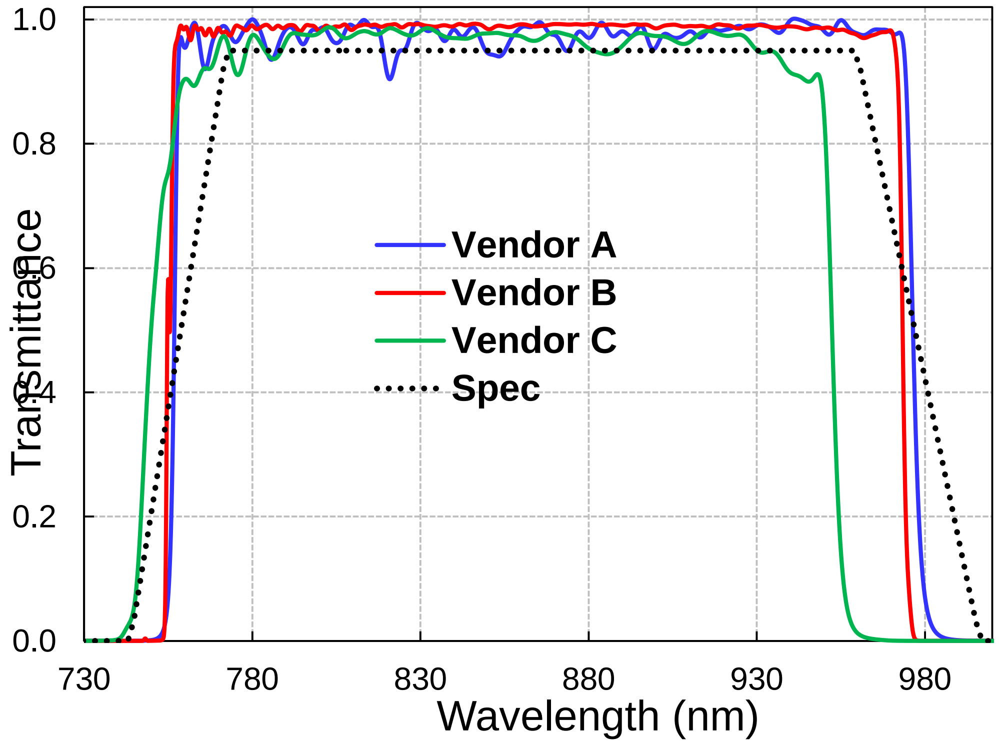


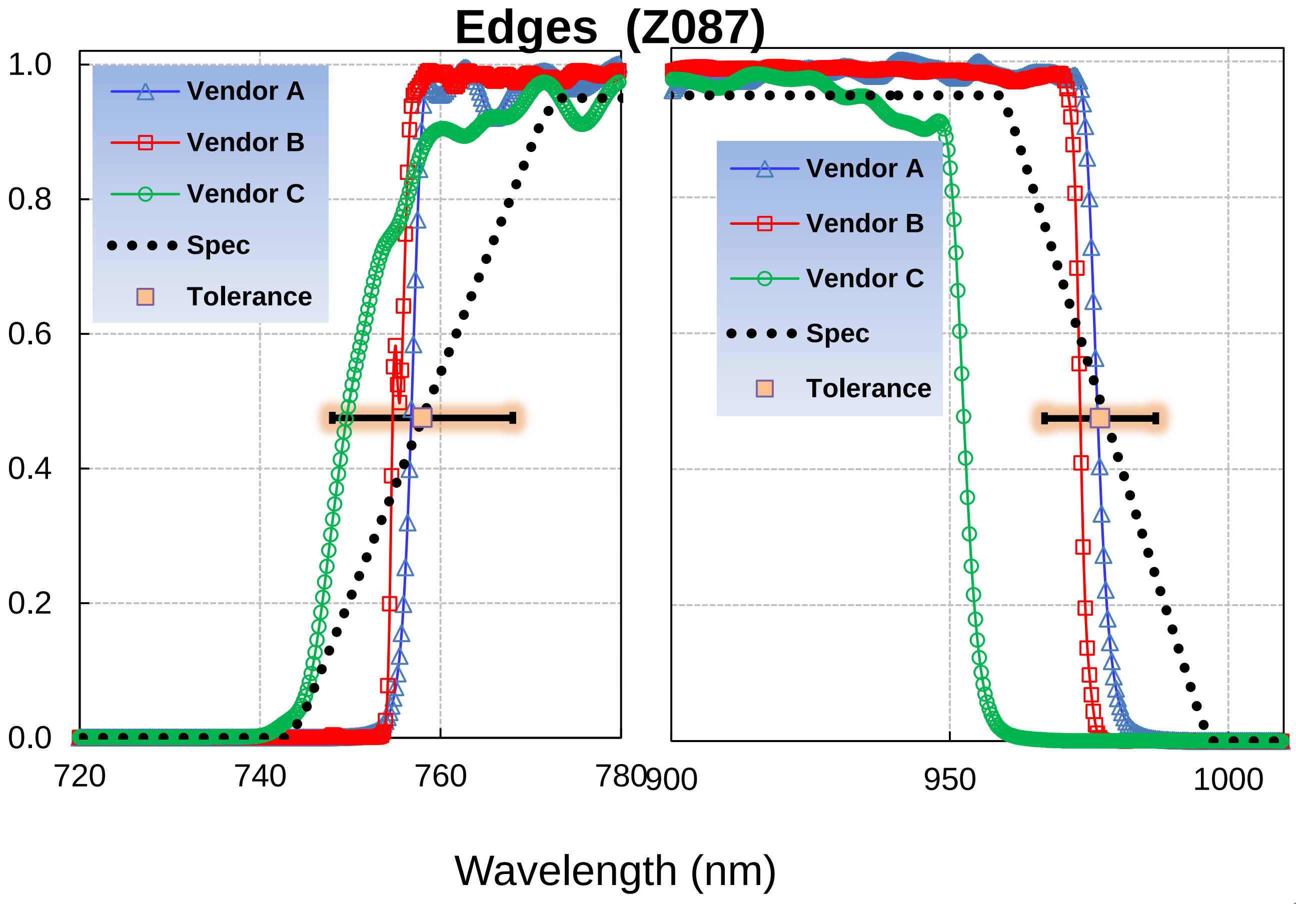


Vendor Comparison: Z087

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

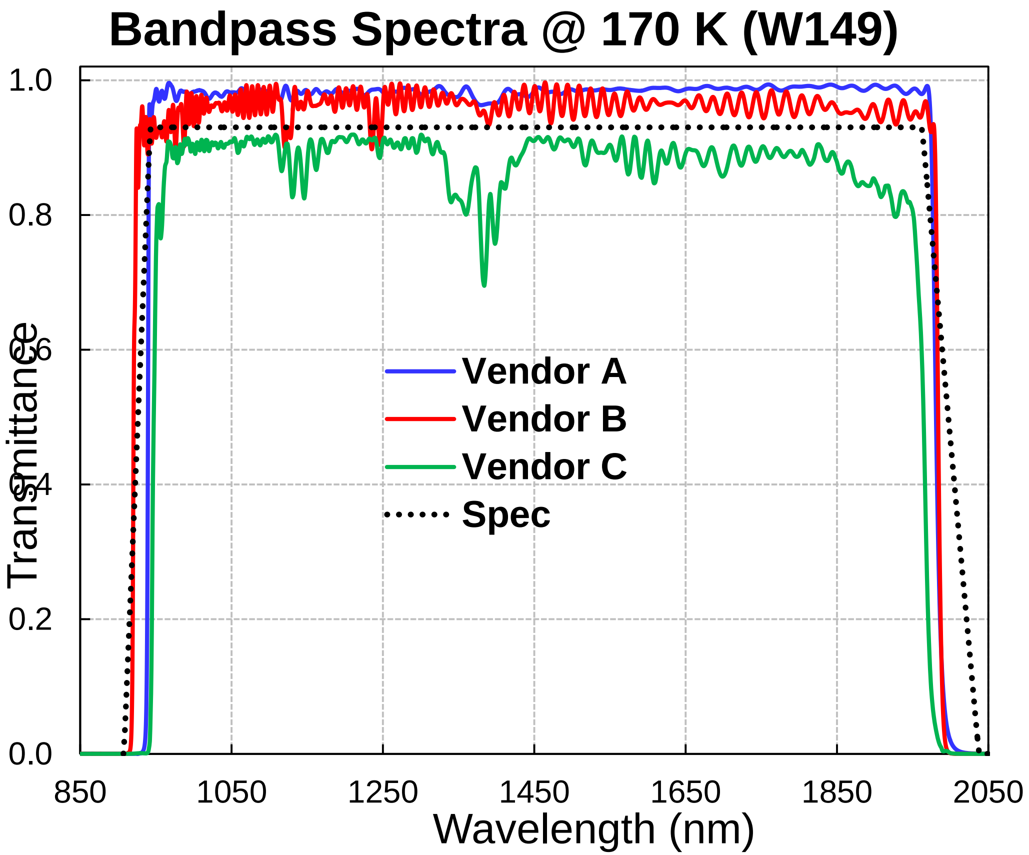
Bandpass Spectra @ 170 K

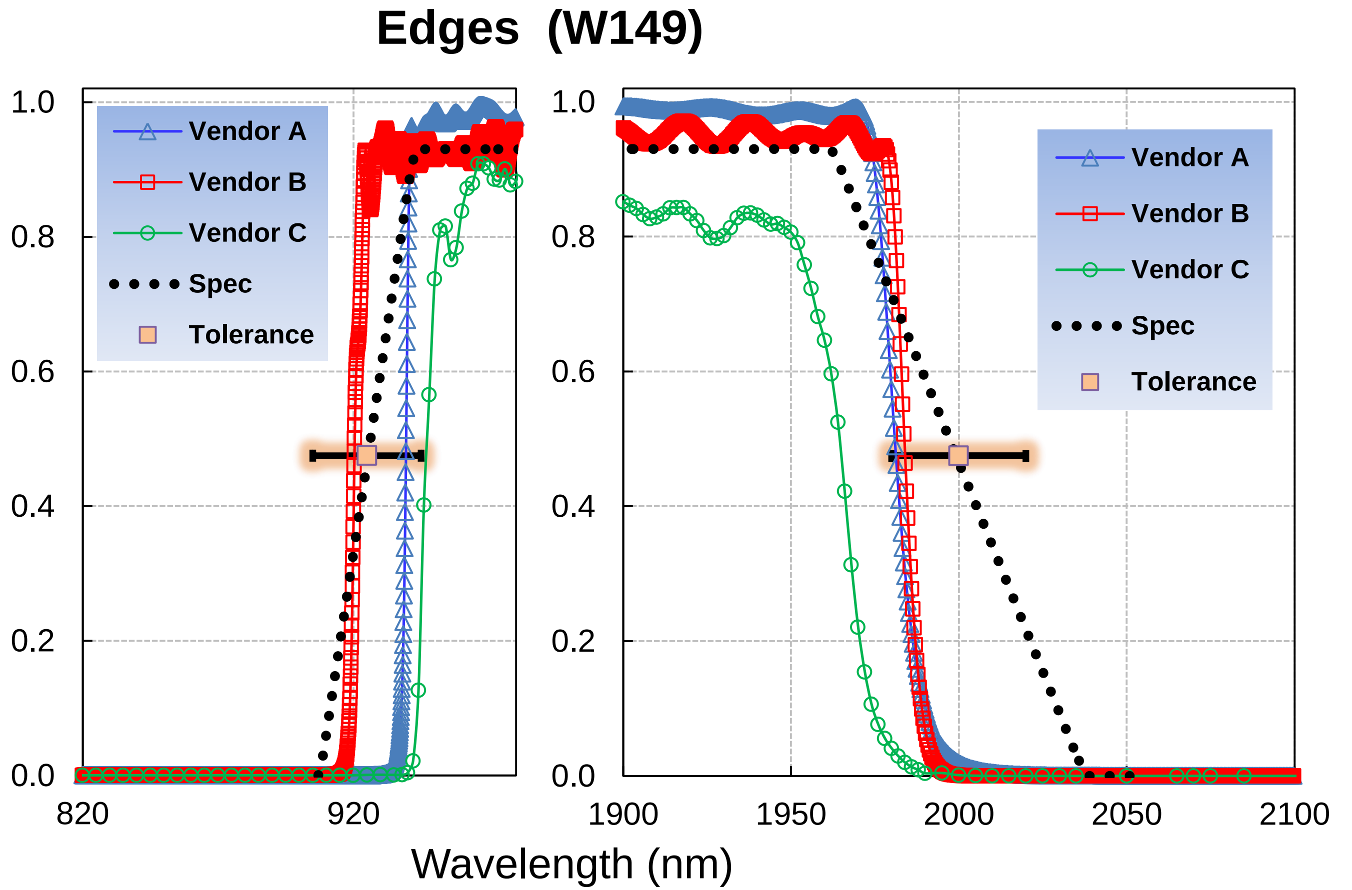




Vendor Comparison: W149

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





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$_{high}$ (%)
Specs.	1,330 ±5	1,980 ±5	1,655 ±5	> 95	< 0.30	< 0.30
A	1,332 (1,333)	1,973 (1,975)	1,652 (1,654)	99	0.77	0.70
B	1,331 (1,332)	1,984 (1,986)	1,657 (1,658)	99	0.40	0.47
C	1,328 (1,329)	1,972 (1,974)	1,650 (1,652)	99	0.73	1.21

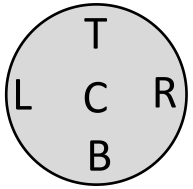
W149	λ_{low} (nm)	λ_{high} (nm)	λ_{center} (nm)	T_{ave} (%)	Slope$_{low}$ (%)	Slope$_{high}$ (%)
Specs.	925 ±20	2,000 ±20	1,465 ±20	> 95	< 3	< 3
A	940 (940)	1,981 (1,983)	1,460 (1,462)	98	0.42	0.77
B	920 (921)	1,984 (1,985)	1,452 (1,453)	98	0.93	0.45
C	945	1,965	1,452 (1,453)	88	1.15	1.83

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

Spatial Uniformity: Grism

Chart Legends:

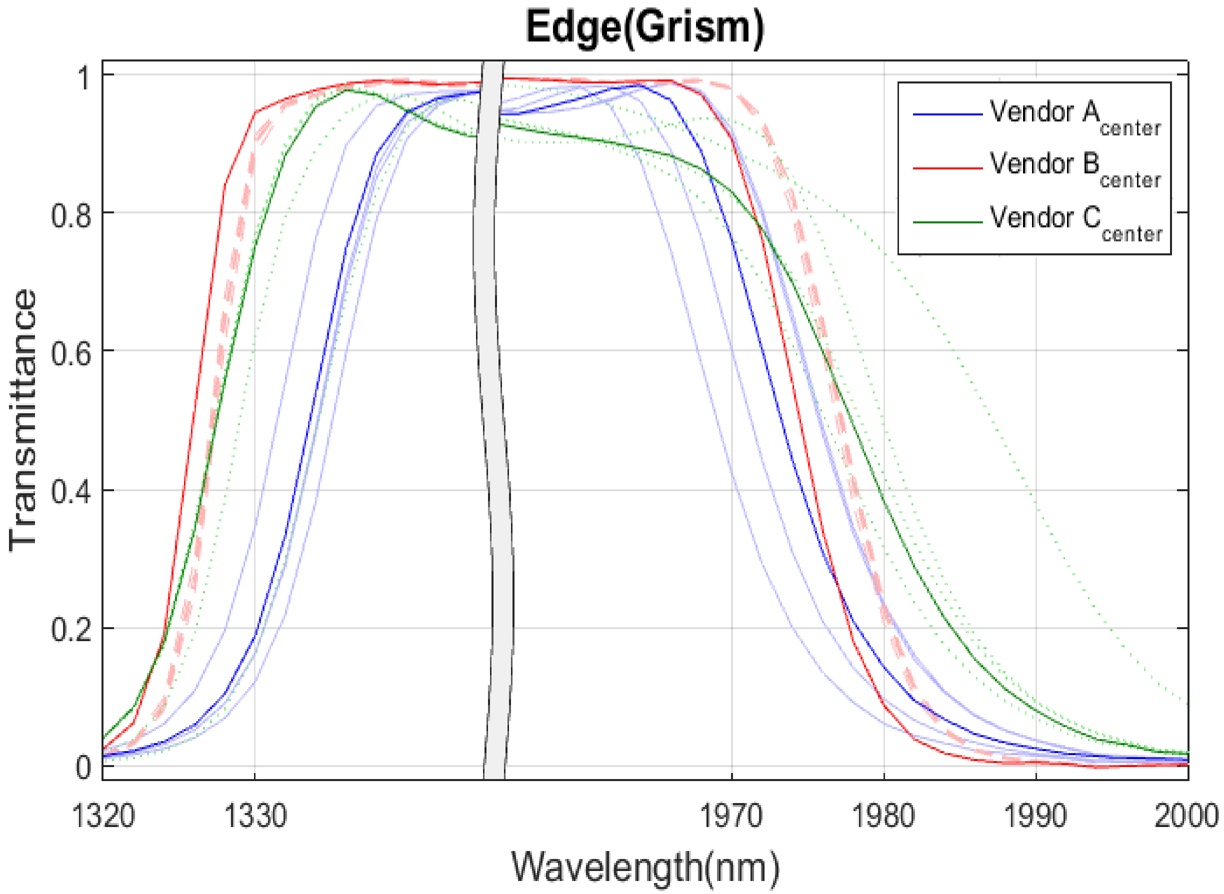
C -> Center
T -> Top
L -> Left
R -> Right
B -> Bottom

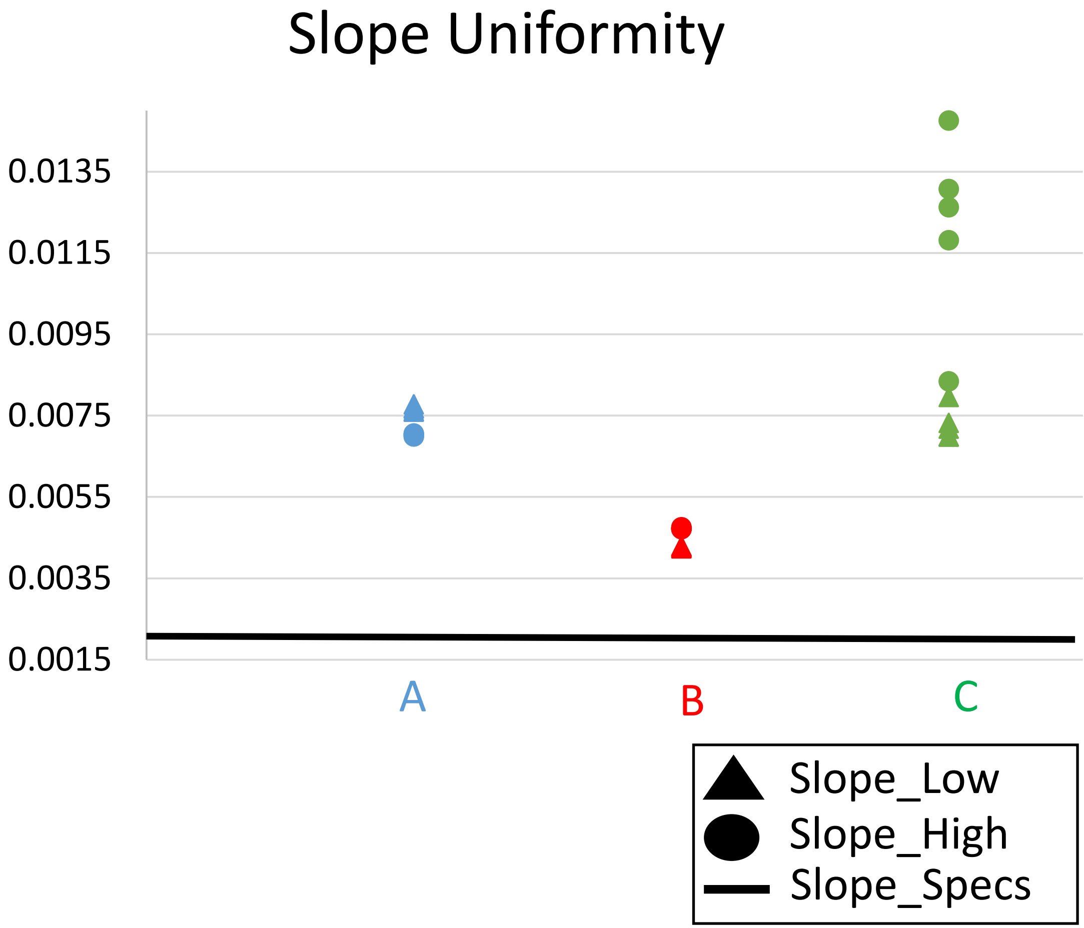


- Transmittance of 110mm filter prototypes were measured over a clear (100 mm) aperture
- Spectrometer beam is rectangular (2x10 mm^2)
- Transmittance was checked in a cross pattern across filter clear aperture
- The values in the middle are the wavelengths for the corresponding parameters
- The values 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 anomaly for vendor C where the 50% FWHM at λ_{high} is -9.3 nm on Top location.

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

Grism Spatial Uniformity





Spatial Uniformity: Z087

- Transmittance of 110mm filter prototypes were measured over a clear (100 mm) aperture
- Spectrometer beam is rectangular (2x10 mm)
- Transmittance was checked in a cross pattern across filter clear aperture
- Variation in bandpass for Z087 is < 1 nm for all three vendors
- One anomaly is seen for vendor A where the 50% FWHM at λ_{high} is 8.8 nm on left side location.

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

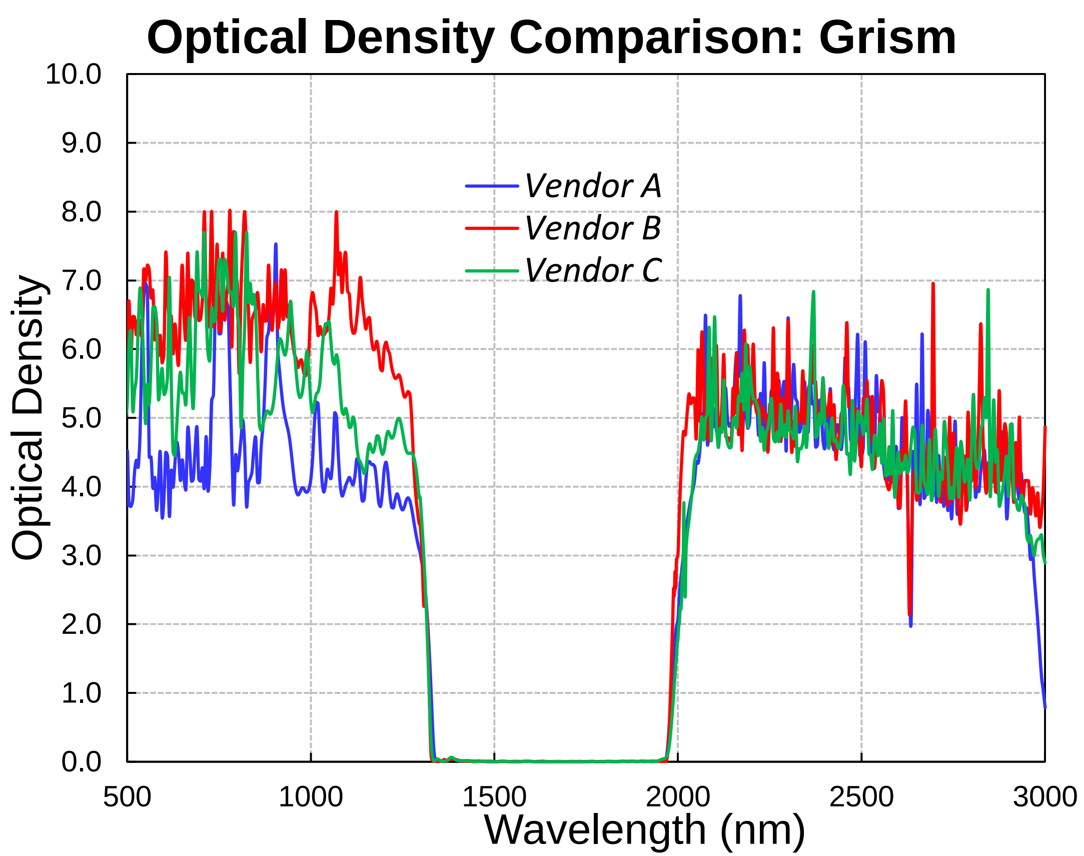
Spatial Uniformity: W149

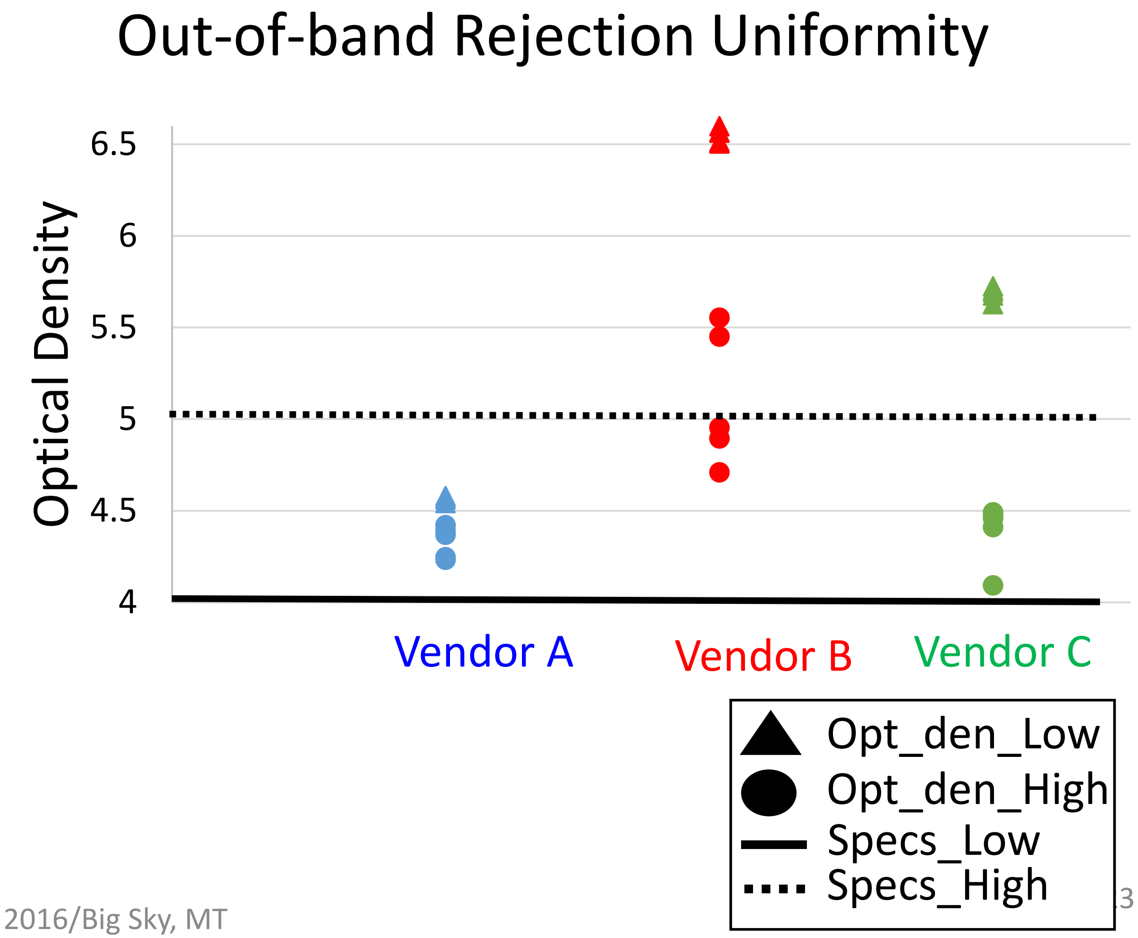
- Transmittance of 110mm filter prototypes were measured over a clear (100 mm) aperture
- Spectrometer beam is rectangular (2x10 mm)
- Transmittance was checked in a cross pattern across filter clear aperture
- Variation in bandpass for W149 is < 2 nm for all three vendors
- One anomaly is seen for vendor A where the 50% FWHM at λ_{high} is -8.2 nm on bottom location.

T / L C R / B	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

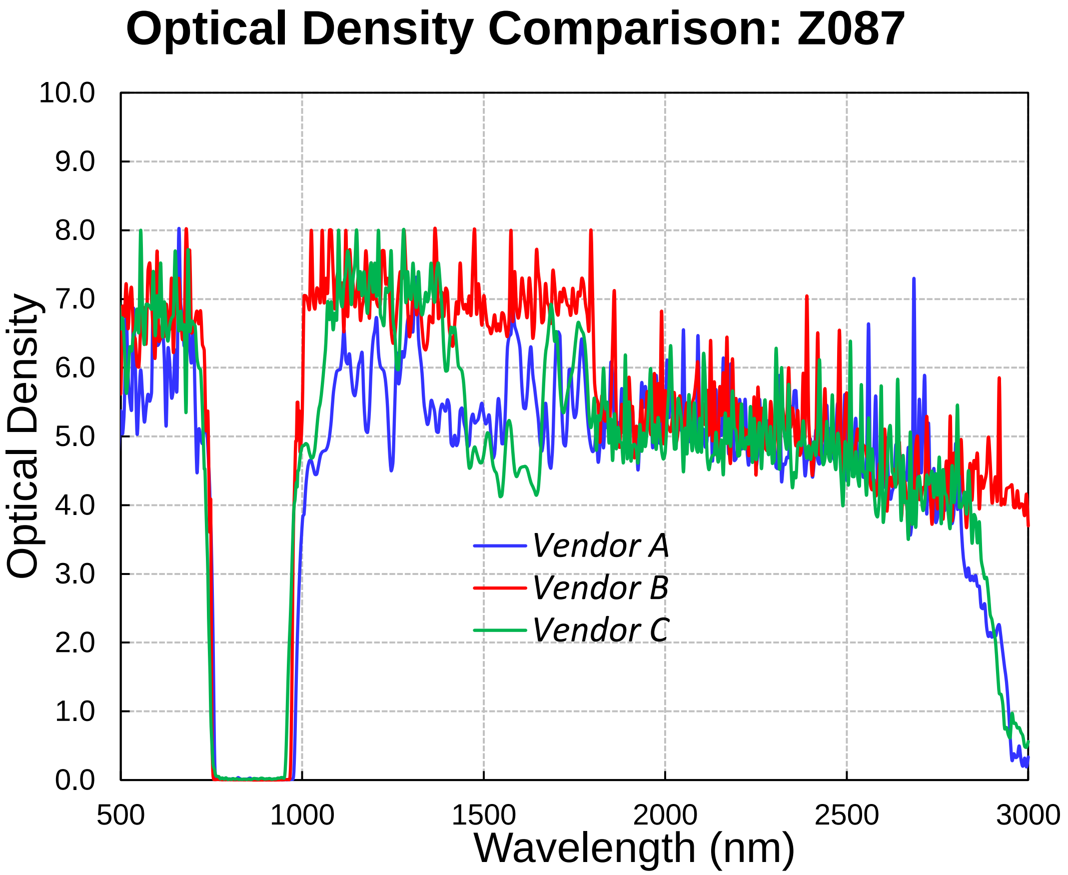
Out-of-Band Blocking: Grism

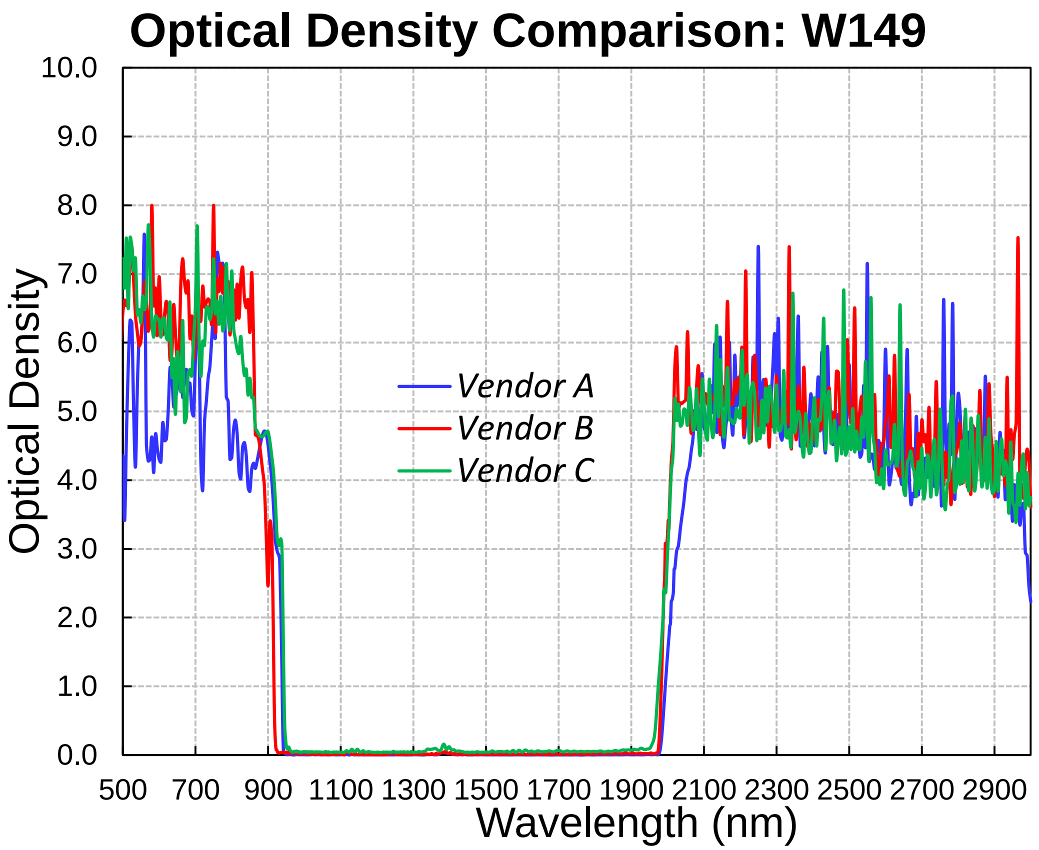
Optical Density = - log10(Transmittance)





Out-of-Band Blocking: Z087 & W149





Conclusions and Lessons Learned

- Spectral characterization of bandpass filters subset WFIRST/AFTA WFI imager showed that most filters met parameters, such as the in-band transmission rates, out-of-band rejections, and sharpness of the edges.
- The transmission curves are very weakly temperature-dependent. The observed shifts were towards low-wavelengths as temperature decreases as expected from thermal contraction effects.
- Coatings vendors have developed new and improved depositions processes that produce denser and longer durability coatings
- The process is more controlled and less “hit or miss” as indicated by the fact that 2 vendors coated all three filters on the first attempt.
- The coatings showed good uniformity over the filter clear aperture of 100mm. This resulted from improvements in deposition processed from demands of the telecom industry in recent past that required good uniformity over large area.
- All filters met out-of-band rejection requirements on the short side of the passband.
- The out-of-band rejections on the long side of the passband were met up to about 2700 nm.

Conclusions and Lessons Learned Cont..

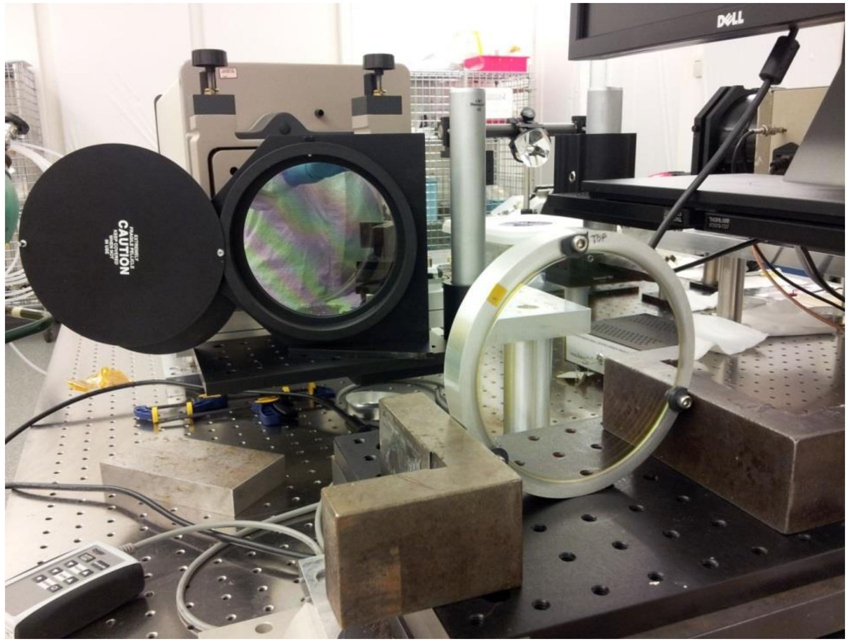
- This lack of blocking performance beyond 2700 nm for all these prototype coatings is compensated with the fact that recently measured detector performance on WFIRST HgCdTe detector arrays showed zero Quantum Efficiency (QE) above 2600 nm.
- Deeper QE measurements beyond cutoff are planned for next detector test phase.
- This combination of filters blocking performance and detector QE will ensure that there is no wavelength long-ward of 2000 nm that will leak through and be a noise contributor.
- This WFIRST/WFI filter procurement and testing exercise provided valuable lessons on the following:
  1) The filter performance requirements are written in a concise way that vendors will easily understand
  2) Provides a realistic baseline in terms of cost and schedule when WFIRST moves in Phase-A activities in the second half of FY16
  3) The development of a credible test plan that will be applicable when procurements of flight optics are done during WFIRST implementation phase

Ambient Figure Error Measurements

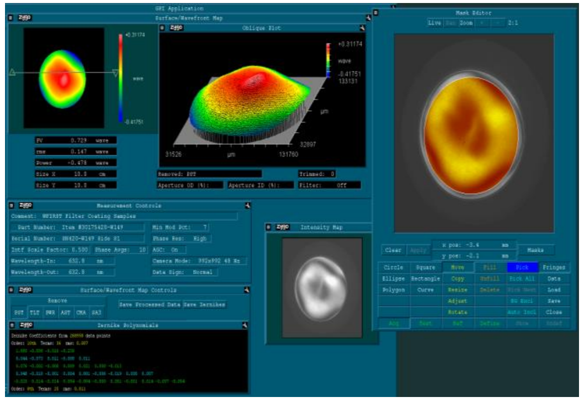
Interferometer:
- Zygo Mark-IV

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

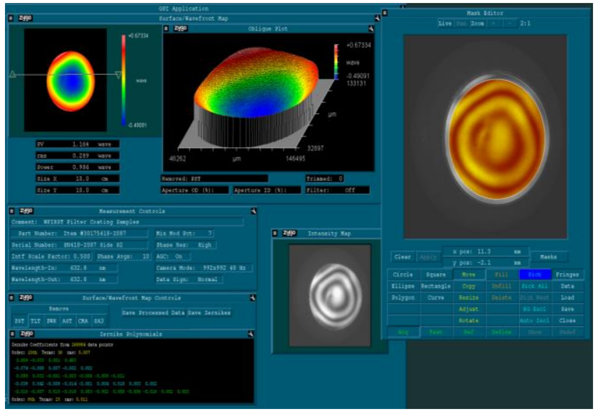
Parts:
- Z087 (SN418-Z087)
  - Item #30175418 Z087 BP Filter V3.2
  - Run #1017-19553-19559
  - Coated 2/20/2015
- GRISM (SN419-GRISM)
  - Item #30175419 GRISM BP Filter V3.2
  - Run #1017-19556-19562
  - Coated 2/23/2015
- W149 (SN420-W149)
  - Item #30175420 W149 WBP Filter V3.2
  - Run #1017-19576-19582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



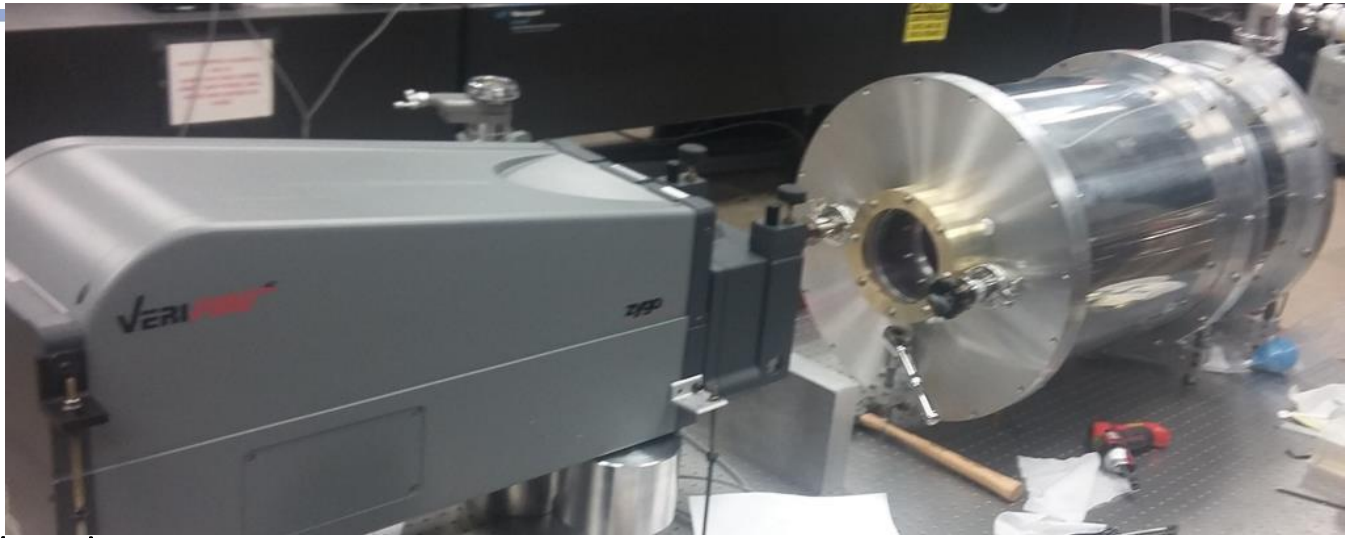
S1



S2



Cryo- Figure Error Measurement Setup



Parts:

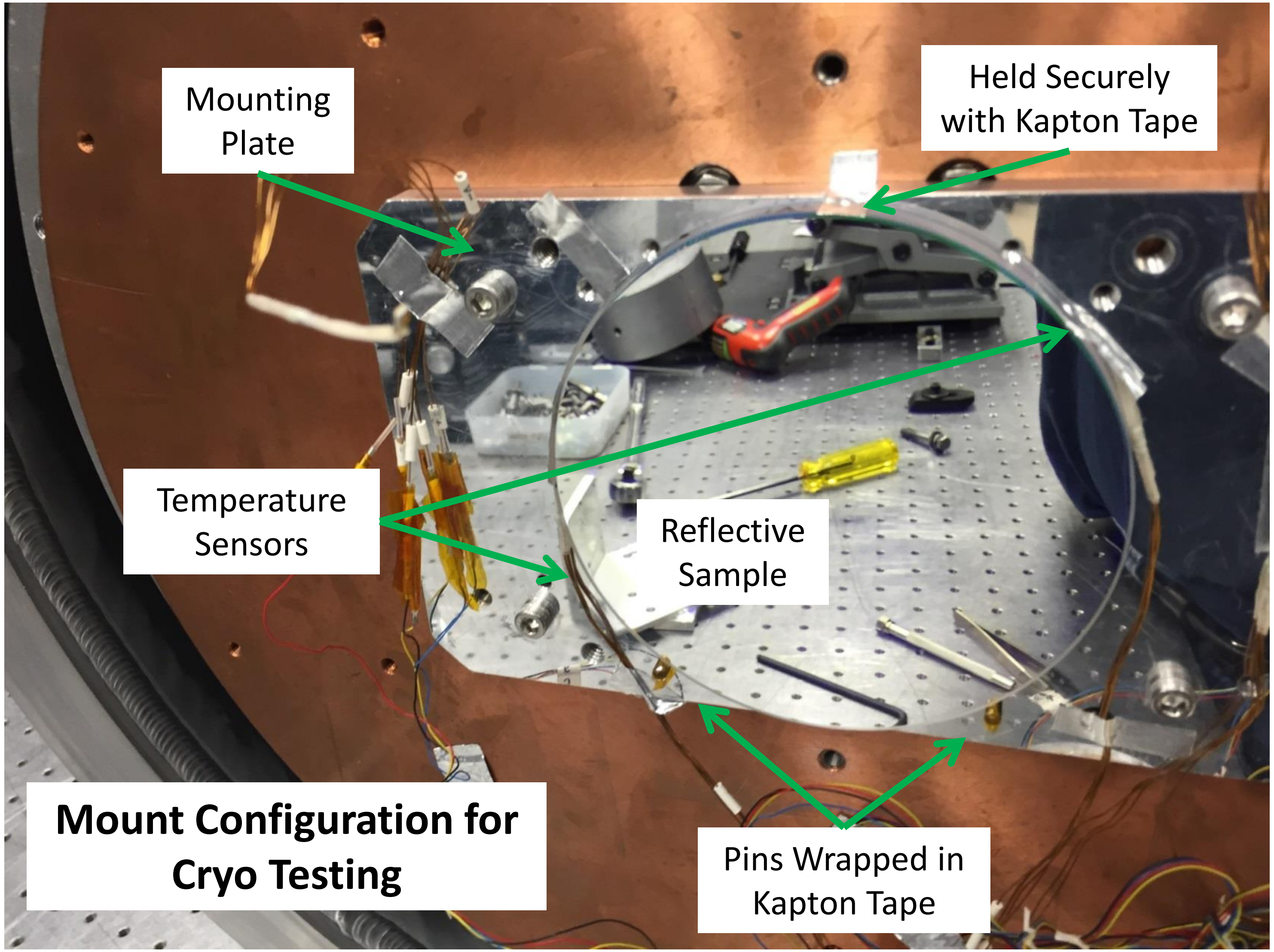
- Z087
  - Vendor A Part # 865-220 OD5 Wideband
  - Vendor B Part # 30175418 Z087 BP Filter V3.2
  - Vendor C Part # F-WB-0013759
- W149
  - Vendor A Part # 1450-1075 OD5 Wideband
  - Vendor B Part # 30175420 W149 WBP Filter V3.2
  - Vendor C Part # (*Pending Delivery*)
- GRISM
  - Vendor A Part # 1650 OD5 Wideband
  - Vendor B Part # 30175419 GRISM BP Filter V3.2
  - Vendor C Part # SN8-GRISM (*Assigned #*)

Filter Coating Specifics:

- Fused Silica substrate
- 110mm diameter OD
- 6mm thick
- Side “S1” = ‘Filter” Side
- Side “S2” = “Mirror” Side

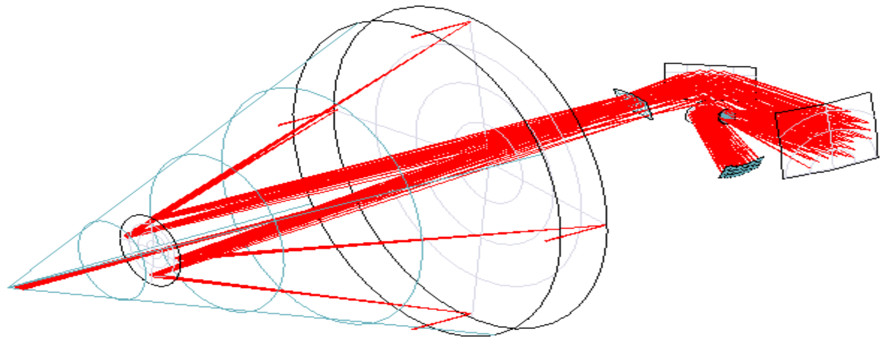
Test Environments:

- Room Temperature, 293K
- Cryo Temperature, 160K


Mounting Plate
Held Securely with Kapton Tape
Temperature Sensors
Reflective Sample
Pins Wrapped in Kapton Tape
Mount Configuration for Cryo Testing

3 coating samples were measured interferometrically, 2 surfaces each
The Fringe Zernike files were imported into Code V
WFE performance was compared to nominal design residual

- Measure surface error:
  - Align sample in mount relative to edge mark
  - Minimize tip & tilt alignment error so that it is not residual in data set
  - Remove Piston only
  - Set scale factor to 0.5 (surface error)
  - Measure S1, rotate mount, measure S2
  - Take 2-3 data sets for each sample
- Post-process data:
  - Sub-aperture data to 105 mm diameter
  - Center mask on interferogram
  - Save data as Zernike file
- Import to Code V
  - Lens file
  - Verify apertures for Filter S1 & S2, CA = 105 mm
  - Place interferograms on respective surfaces
  - Scale for wavelength on S1 & S2 and for rotation direction of S2
  - Compensate error with focus adjustment
  - Compare WFE at 19 zoom positions to residual error

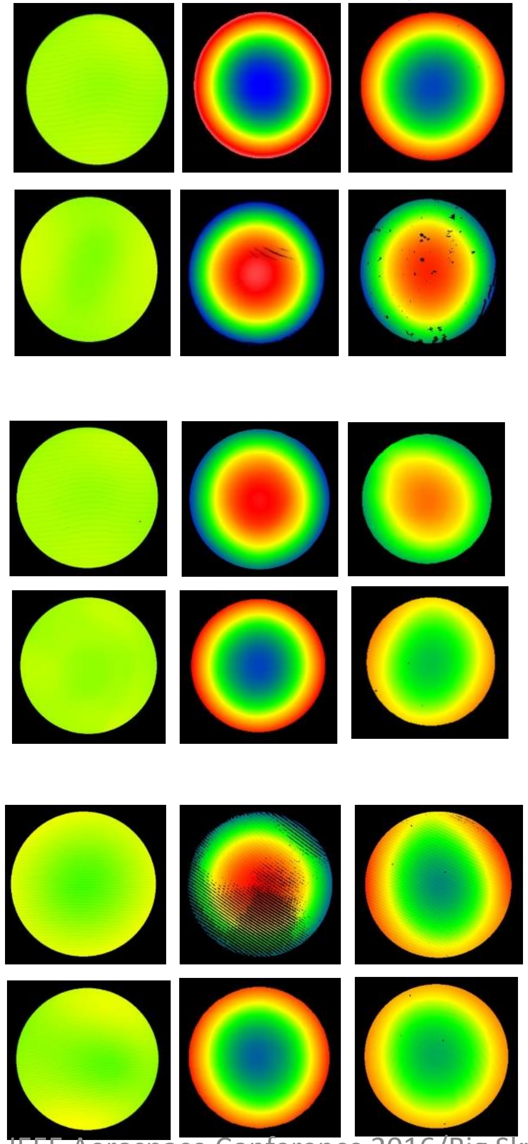


AFTA-WIM-v5-0-6-140926.len

Compare Results:
Uncoated Substrate at ambient 293 K (+20C)
Coated at ambient at 293K (+20C) (B5 W059)
Cryo at 160K (-113C) (B7 013)

Vendor A

Uncoated Ambient Cryo



Z087 Filter
Substrate SN/09

S1

S2

Scale: ±5.5 λ

W149 Filter
Substrate SN/04

S1

S2

Scale: ±3.0 λ

GRISM Filter
Substrate SN/05

S1

S2

Vendor A Surface Error: Uncoated, Coated @ Ambient & Cryo

Surface Error: RMS, Power in Waves for λ = 632.8nm

Vendor A	Uncoated		Ambient (293K)		Cryo (160K)	
	RMS Surface	Power	RMS Surface	Power	RMS Surface	Power
Z087, SN/09						
Surface 1	0.082	0.079	3.202	11.093	2.430	8.418
Surface 2	0.143	0.287	2.951	-10.250	2.275	-7.899
W149, SN/04						
Surface 1	0.094	0.187	1.391	-4.802	0.806	-2.738
Surface 2	0.044	0.082	1.349	4.666	0.645	2.168
GRISM, SN/05						
Surface 1	0.109	0.359	0.836	-2.968	0.627	2.049
Surface 2	0.092	0.179	0.784	2.705	0.488	1.680

Vendor B

Uncoated | Ambient | Cryo

Z087 Filter
Substrate SN/03

S1
S2

Scale: ±1.0 λ

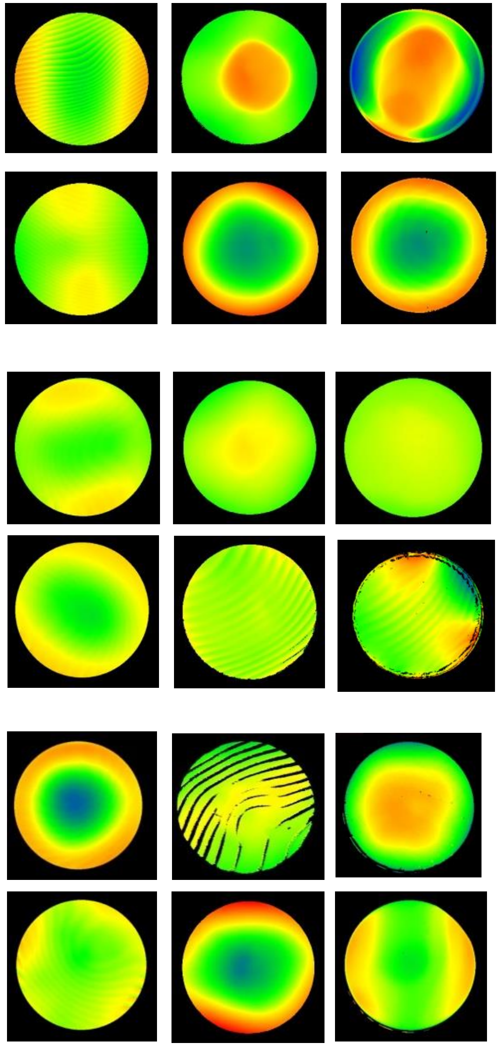
W149 Filter
Substrate SN/07

S1
S2

Scale: ±1.0 λ

S1
S2

Scale: ±1.0 λ

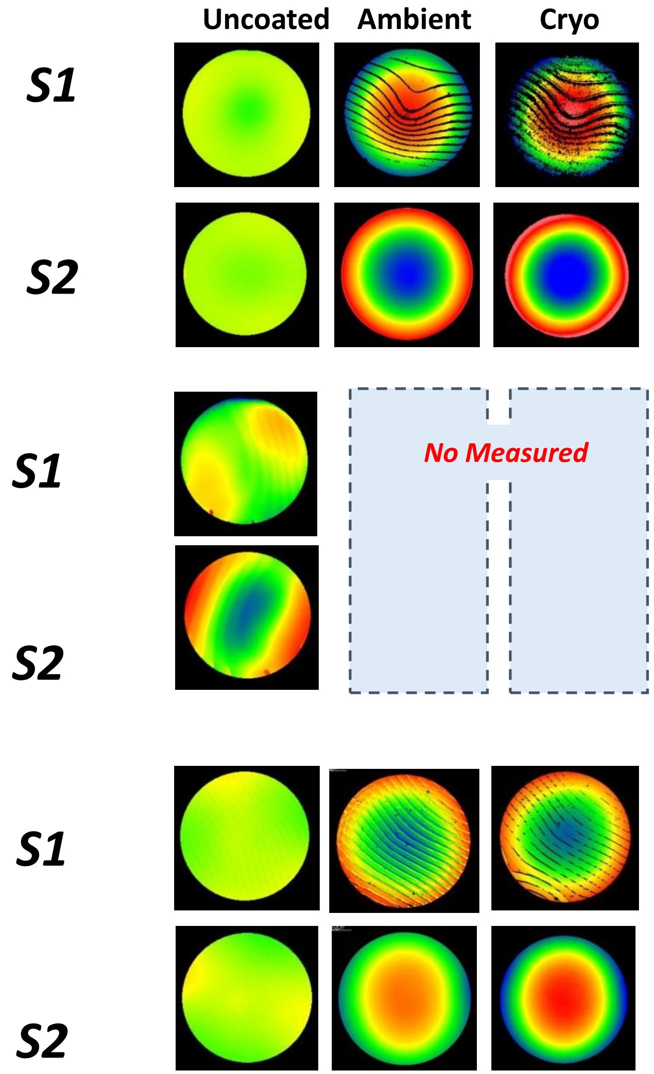


Vendor B Surface Error:
Uncoated, Coated @ Ambient & Cryo

Surface Error: RMS, Power in ***Waves for λ = 632.8nm***

Vendor B	Uncoated		Ambient (293K)		Cryo (160K)	
	RMS Surface	Power	RMS Surface	Power	RMS Surface	Power
Z087, SN/03						
Surface 1	0.161	0.407	0.211	-0.650	0.370	-0.950
Surface 2	0.089	-0.076	0.316	1.077	0.292	1.010
W149, SN/07						
Surface 1	0.184	0.384	0.162	-0.528	0.079	-0.260
Surface 2	0.265	0.845	0.077	0.097	0.456	-0.130
GRISM, SN/06						
Surface 1	0.301	0.983	0.099	-0.215	0.234	-0.807
Surface 2	0.080	0.224	0.316	1.002	0.150	0.326

Vendor C



Z087 Filter
Substrate SN/09
Scale: ±4.0 λ

W149 Filter
Substrate SN/04
Scale: ±0.5 λ

GRISM Filter
Substrate SN/05
Scale: ±1.5 λ

Vendor C Surface Error: Uncoated, Coated @ Ambient & Cryo

*Surface Error: RMS, Power in **Waves for λ = 632.8nm***

Vendor C	Uncoated		Ambient (293K)		Cryo (160K)	
	RMS Surface	Power	RMS Surface	Power	RMS Surface	Power
Z087, SN/08						
Surface 1	0.186	0.495	0.211	-0.650	0.370	-0.950
Surface 2	0.093	0.241	0.316	1.077	0.292	1.010
W149, SN/01 – *No Measured*						
Surface 1	0.084	-0.052	*X*	*X*	*X*	*X*
Surface 2	0.186	0.506	*X*	*X*	*X*	*X*
GRISM, SN/02						
Surface 1	0.069	-0.010	0.195	0.348	0.554	1.901
Surface 2	0.091	-0.096	0.243	0.573	0.707	-2.414

System Impact

Interferograms Placed into
Optical Model:

Ambient at 293K (+20C)
Cryo at 160K (-113C)

Z087 Coating

WIM System Impact at Ambient & Cryo

*Change in System-Level WFE = **MAX Δ RMS WFE for λ = 1.0μm***

Full Filter Data, then Remove Substrate Errors

		Vendor A (SN/09)		Vendor B (SN/03)		Vendor C (SN/08)	
		ΔWFE (μm)	ΔFocus (μm)	ΔWFE (μm)	ΔFocus (μm)	ΔWFE (μm)	ΔFocus (μm)
AMBIENT No Refocus	Filter Errors	0.062	--	0.033	--	0.071	--
	Remove Substrate	0.042	--	0.024	--	0.049	--
Using Refocus	Filter Errors	0.024	113	0.014	60	0.035	115
	Remove Substrate	0.018	77	0.020	24	0.041	43
CRYO No Refocus	Filter Errors	0.080	--	0.067	--	0.091	--
	Remove Substrate	0.092	--	0.072	--	0.067	--
Using Refocus	Filter Errors	0.067	72	0.068	-5	0.058	131
	Remove Substrate	0.088	37	0.072	-41	0.058	59

W149 Coating

WIM System Impact at Ambient & Cryo

Change in System-Level WFE = ***MAX Δ RMS WFE for λ = 1.0µm***

Full Filter Data, then Remove Substrate Errors

		Vendor A (SN/04)		Vendor B (SN/07)		Vendor C (SN/01)	
		ΔWFE (µm)	ΔFocus (µm)	ΔWFE (µm)	ΔFocus (µm)	ΔWFE (µm)	ΔFocus (µm)
AMBIENT No Refocus	Filter Errors	0.008	--	0.022	--	*No Measured*	
	Substrate Removed	0.025	--	0.120	--		
Using Refocus	Filter Errors	0.007	-20	0.008	-50		
	Substrate Removed	0.021	-49	0.064	-191		
CRYO No Refocus	Filter Errors	0.039	--	0.091	--		
	Substrate Removed	0.045	--	0.150	--		
Using Refocus	Filter Errors	0.023	-67	0.089	-40		
	Substrate Removed	0.013	-96	0.117	-181		

GRISM Coating

WIM System Impact at Ambient & Cryo

Change in System-Level WFE = ***MAX Δ RMS WFE for λ = 1.0µm***

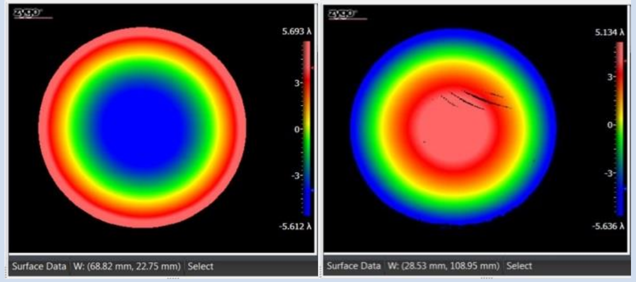
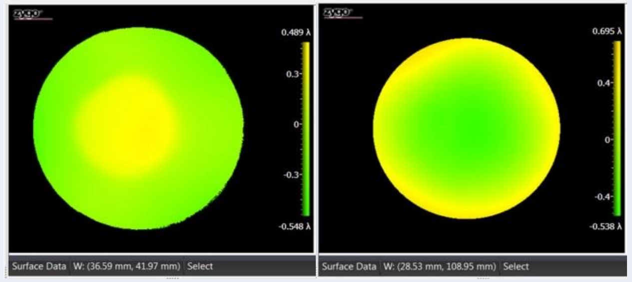
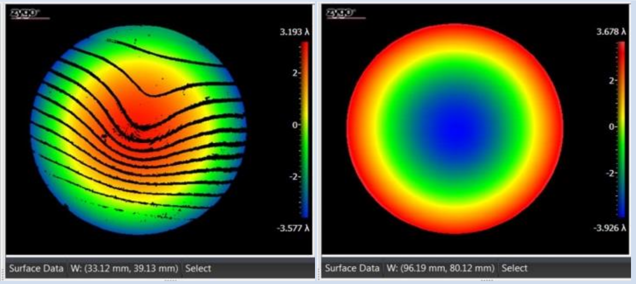
Full Filter Data, then Remove Substrate Errors

		Vendor A (SN/05)		Vendor B (SN/06)		Vendor C (SN/02)	
		ΔWFE (µm)	ΔFocus (µm)	ΔWFE (µm)	ΔFocus (µm)	ΔWFE (µm)	ΔFocus (µm)
AMBIENT No Refocus	Filter Errors	0.025	--	0.046	--	*No Measured*	
	Remove Substrate	0.059	--	0.017	--		
Using Refocus	Filter Errors	0.019	-33	0.012	93		
	Remove Substrate	0.035	-94	0.016	-46		
CRYO No Refocus	Filter Errors	0.243	--	0.044	--	0.035	--
	Remove Substrate	0.215	--	0.106	--	0.037	--
Using Refocus	Filter Errors	0.053	428	0.031	-64	0.028	-60
	Remove Substrate	0.072	367	0.030	-202	0.032	-48

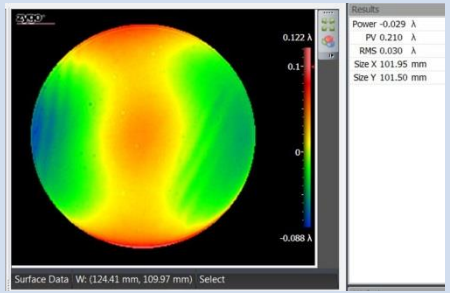
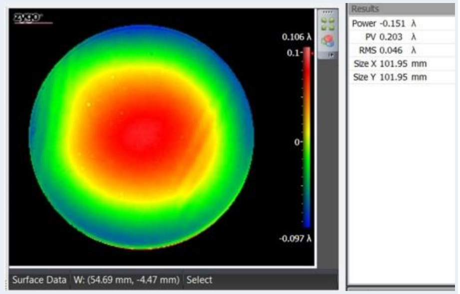
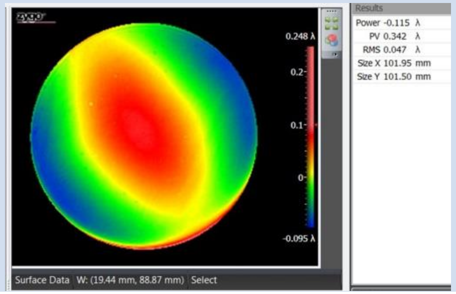
Transmitted Wavefront: Ambient Results

- The Sample Bandpass Coatings have been evaluated for their impact on the WFIRST-AFTA Wide Field Channel.
- Measurements of the Transmitted Wavefront
    - Double-pass @ 1550 nm
- Wavefront applied to Wide Field Channel, Evaluated impact of imaging across the field:
    - Wavefront Error
    - Focus Shift
    - Re-focused Wavefront Error

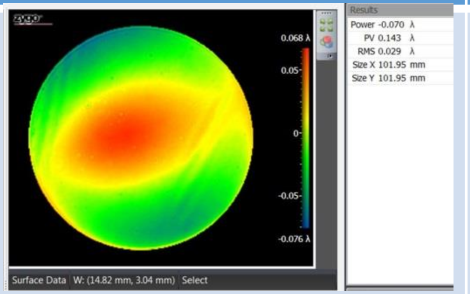
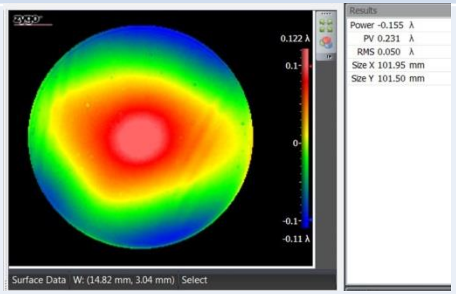
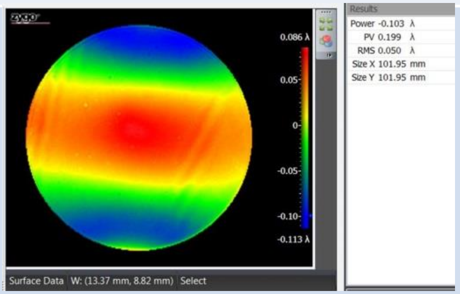
Z087 Results (from ***Reflected*** WFE)

	Interferogram (S1-S2) Scale: ± 4.0 Waves	WFE Delta (RMS)	WFE Delta (Focus Removed)	Focus Shift
Vendor A Z087 SN-09		62 nm	24 nm	113 µm
Vendor B Z087 SN-03		33 nm	14 nm	60 µm
Vendor C Z087 SN-08		71 nm	35 nm	115 µm

W149 Results

	Interferogram Scale: ± 0.1 Waves	WFE Delta (RMS)	WFE Delta (Focus Removed)	Focus Shift
Vendor A W149 SN-04		31 nm	31 nm	9 µm
Vendor B W149 SN-07		48 nm	10 nm	102 µm
Vendor C W149 SN-01		52 nm	44 nm	67 µm

Grism Results

	Interferogram Scale: ± 0.1 Waves	WFE Delta (RMS)	WFE Delta (Focus Removed)	Focus Shift
Vendor A Grism SN-05		30 nm	21 nm	42 µm
Vendor B Grism SN-06		53 nm	22 nm	96 µm
Vendor C Grism SN-02		59 nm	46 nm	65 µm

Lessons Learned

In Future Sample Evaluations:

- Single overseer of all testing/Record book
- Minimized # of testing operators
- More explicit scribed Markings (SN#, Fiducials, S1/S2)
- Measure Transmitted Spectrum and Wavefront of Substrates
- Verify Substrate Material Grade
- Use 8mm thick substrates
- Maintain uncoated substrate control sample
- Measure Transmission cold (Facility?)

Projected Specifications

- Based on simulations of Filter WFE in WFC
  - Total Fabrication Budget: 18.3 nm (as of 1/12/2016)
  - Correlates to ~55nm RMS Surface Figure Error (S1+S2) for combination of Zernikie Terms
- Coating Specifications (cryo) to include:
  - Per Surface Distortion (Power removed) (TBD)
  - Maximum Bending (Matched Power both surfaces) (TBD)
  - Cryo Transmitted wavefront (<18.3 nm RMS, power removed)
    - Can be slightly higher in long bands, wideband, and Grism
  - Focus shift: considered as filter-to-filter focus deltas. (TBD, Band dependent)
    - (Note: 10µm focus = 5 nm RMS WFE)
- EUCLID Comparison:
  - 130mm dia., 12 mm thick, plano-convex (10 m radius)
  - Substrate Vendor (Winlight, France) working in concert with with ESA consortium-selected coating vendor and Max Plank Institute for meansurements
  - Performance: 7.5 nm Substrate WFE, Final coated cryo WFE: <15 nm

Projected Specifications

- Based on simulations of Filter WFE in WFC
  - Total Fabrication Budget: 18.3 nm (as of 1/12/2016)
  - Correlates to ~55nm RMS total Surface Figure Error(s) for combination of Spherical, Astigmatism, Coma, Trefoil
- Coating Specifications (delta after coating, cryo) to include:
  - Per Surface Distortion (Power removed) (?)
  - Maximum Bending (Power both surfaces) (?)
  - Transmitted wavefront (<18.3 nm RMS)
    - Power removed, but considered as filter-to-filter focus deltas.
    - Focus Shift (Note: 10µm focus shift = 5 nm RMS Power Wavefront)

Vendor Considerations

- For Flight Filters, meniscus substrates should be tested in “flight-like” converging beam or custom curved retro mirror and cryo-capable.
- Should consider that the substrate vendor would be responsible to coordinate with coating vendor directly.
- All testing could use the same unbroken cryo-capable setup that was used to fabricate and test the substrates
  - Fixed Filter Mounting Reference Surface
  - Fixed reference beam, reference sphere and retroreflector
  - Stable Systemic residuals