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Performance of the WFC3 Replacement IR Filters

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ABSTRACT

This report summarizes the performance of the three new replacement filters (F110W, F125W, and F140W) installed in the WFC3 IR filter wheel; the two new IR grisms are discussed in a separate report. The intent is to record for future reference the as-built properties of the new filters, providing an addendum to the original WFC3 document which presented the characteristics of the IR filter set in the instrument at that time (Lupie et al. WFC3 ISR 2003-07).

Introduction

The original IR filters procured for WFC3 fully satisfied the requirements at the time of their installation in the filter wheel (Lupie et al. 2003) and the filters performed as expected during instrument-level ground testing. However, instrument-level ground testing revealed that the HgCdTe IR detector suffered from particle-induced luminescence. Subsequent radiation testing of non-flight parts determined that the luminescence arises within the detector's CdZnTe substrate and that the problem can be effectively eliminated by removing the substrate (Waczynski et al. 2005). As a consequence, a new substrate-removed IR detector for WFC3 is under development. But, in addition to reducing the luminescence, removal of the substrate also results in a significant increase in the quantum efficiency blueward of 800nm (Kimble et al. 2006), which is an issue for two of the original IR filters. Due to schedule constraints at the time of their manufacture, the IR filters F110W and F125W had been constructed on fused silica with the understanding that the blue cutoff of the detector would provide the necessary blocking (the remainder of the IR filters, as well as the grisms, had been made on IR-transmitting glass which has no significant transmission below 800 nm). Since the new detector no longer provides the blocking required in the blue, new versions of these two filters were manufactured using Hoya IR80, an IR color glass which does not transmit below 800 nm.

In addition, a third filter replacement has occurred since the original IR filter installations: F140W has been installed in place of F093W. The latter was originally intended to be used in conjunction with an optical laser in order to align the IR channel but new alignment techniques no longer require the F093W. Given that there was considerable scientific justification for an F140W (Brown & Baggett 2006) and a viable F140W filter was already in-hand, the F093W was replaced with F140W.

In total, three new replacement filters now reside in the WFC3 IR filter wheel: F110W, F125W, and F140W. The remainder of this report presents the primary performance characteristics of these new filters; the two IR grisms, which have also been replaced, are discussed in a separate report (Baggett et al. 2007).

Characterization and Evaluation of Candidates

The characterization tests performed on the replacement filter candidates in the lab have been based upon those used for the original IR filters (Boucarut et al. 2001) and included inspections, spectral scans. verification of physical dimensions, wedge, wavefront quality, and focus shift. Further tests were added to the suite in order to verify compliance with the CEI ghost specification and the environmental requirements; the full set of characterization tests run on the IR replacement filters is described in Baggett et al. (2006). Individual lab reports detailing all test procedures and results for each filter (approved flight and spares, as well as some filters not chosen for flight) are archived on the private Goddard Space Flight Center WWW site and are available upon request.

The WFC3 team (STScI and GSFC) as well as the SOC (Science Oversight Committee) evaluated all candidate replacement filter test data for compliance with the filter requirements (Boucarut 2003, CEI spec, and SER-OPT 015). The final determination of acceptable filter properties was made by the WFC3 SOC, who assessed the as-built filter characteristics in light of the overall science goals of WFC3 and decided how much deviation was tolerable for a given specification and which, if any, particular replacement filter to fly.

Filter Throughput Data

In- and out-of-band spectral scans of the replacement filter candidates were performed at Goddard Space Flight Center; details of the test setup and procedure can be found in

Quijada et al. (2006). The differences between in- and out-of band spectral measurements and requirements were evaluated on a case-by-case basis and in light of each filter's characteristics and performance as a whole. Occasional nonconformities of a filter to the requirements were approved by the SOC given excellent performance characteristics in other areas.

The spectral scans of the replacement filters chosen for flight are presented, for both room and expected operating temperatures in Appendix A. Table 1 and Table 2 below summarize the results from the spectral measurements taken at 243K (except for the out-of-band results for F140W, which were taken at 296K); wavelengths are air. These filters have now replaced their equivalent originals in the IR filter wheel; as such, the properties listed in the tables here replace those listed in ISR 2003-07 (Lupie et al. 2003). The in- and out-of-band filter spectral data of the new replacement flight filters have also been incorporated into the STScI Synthetic Photometry, or SYNPHOT, tables for use in the WFC3 calibration pipelines and into the web-based exposure time calculator (Brown 2006).

Table 1 presents the primary in-band 243K throughput properties of the replacement filters selected and approved for flight. There are three rows per filter, showing the measurements of the as-built flight element, the original specifications, and the difference between the measurements and the specification. Wavelengths are air, in units of nm, with a measurement accuracy +/- 0.5nm. In addition to the peak and edge transmission requirements, the specifications called for a minimum of ripple within the 90% passband; that is, transmission within the 90% passband should not fall below 90%, which the replacements all easily satisfy. Definitions of the spectral quantities shown in Table 1 originated in the GSFC specification document (Boucarut 2003) and for convenience, are repeated here.

Table 2 presents the requirements and measured 243K values for out-of-band (OOB) transmission of the replacement filters selected and approved for flight (except for F140W, where OOB was measured at 296K only). Longward of the passband, from the red-side max wavelength to 1800nm, the wide-band filter transmission is required to be less than 10^{-4} absolute. Likewise, shortward of the blue-side max wavelength, the OOB transmission is required to be less than 10^{-4} absolute. The three filters easily satisfy the specifications except the 700-800 nm regime in F140W, where the transmission approaches 10^{-4} (a feature discussed in more detail in Appendix A).

<u>Columns in Table 1 (in-band spectral scans)</u>

Wavelengths are air.

Filter name: identifier used in on-orbit and ground systems.

Part Number: unique identifier of available candidates for a given filter identifying the specific replacement part ultimately chosen for flight.

λ_0 : the filter's central wavelength, given by = [λ_{-50} + λ_{+50}]/2.
FWHM: full-width at the half-transmission points, is defined as ([λ_{-50} - λ_{+50}]).
λ_{-01} , λ_{+01}: wavelengths on either side of the central wavelength where the transmission is <1% absolute and remains below 1% for wavelengths shortward and longward of λ_{-01} and λ_{+01}, respectively.
λ_{-50} , λ_{+50}: wavelengths on either side of the passband where the transmittance equals 50% of the peak and remains less than 50% of the peak shortward and longward of λ_{-50} and λ_{+50} , respectively.
λ_{-90}, λ_{+90} : wavelengths between which the transmission is greater that 90%.
Ave T: minimum acceptable value for absolute transmission, averaged from λ_{-90} to λ_{+90}.
Comment: identifies row as design specification, measured values, or the difference.

Table 1. In-band throughput performance of the IR replacement flight filters; three rows are listed for each filter: design specifications, the measured values, and the difference between the two (meas-spec); wavelengths are in nm. Instances where no requirements were specified for a given quantity are indicated by '-'.

filter name	part num	λ_0	avg T (%)	FWHM	λ_{-50}	λ_{+50}	λ_{-90}	λ_{+90}	λ_{-01}	λ_{+01}	comment
F110W	311	1149.7	95.96	503.5	897.9	1401.5	918.2	1395.3	881.7	1411.7	meas
		1150.0	95.00	500.0	900.0	1400.0	--	--	--	--	spec
		-0.3	+0.96	+3.5	-2.1	+1.5	--	--	--	--	dev
F125W	010	1249.0	96.35	303.2	1098.2	1399.7	1104.0	1395.2	1083.8	1413.5	meas
		1250.0	98.00	300.0	1100.0	1400.0	111.3	1388.7	1086.2	1413.8	spec
		-1.0	-1.65	3.2	-1.8	-0.3	-7.3	+6.5	-2.4	-0.3	dev
F140W	001	1397.3	97.98	394.7	1200.0	1594.7	1203.7	1590.1	1184.8	1612.9	meas
		1400.0	98.00	400.0	1200.0	1600.0	1226.1	1573.9	1168.1	1631.9	spec
		-2.7	-0.02	-5.3	0.0	-5.3	-22.4	+16.2	+16.7	-19.0	dev

<u>Columns in Table 2 (out-of-band spectral scans)</u>
Wavelengths are air.
Filter name: identifier used in on-orbit and ground systems.
Part Number: unique identifier of available candidates for a given filter, identifying the specific replacement part ultimately chosen for flight.
Wavelength: passband boundary wavelength (OOB regions are defined as red-side max wavelength out to 1800nm, and shortward of blue-side max wavelength).

T_{spec}: transmission requirement for the given OOB region.

T_{meas}: transmission measured in the given OOB region.

Table 2. Out-of-band throughput performance longward of the passband in the IR replacement flight filters; wavelengths are in nm. Specifications are from the IR filter specification document (GSFC P-442-3402). Blue side wavelength is the red limit of the OOB range shortward of the passband; red side wavelength is the blue limit of the OOB range longward of the passband.

		blue side			**red side**		
filter name	**part num**	**wavelength**	**T, spec**	**T, meas**	**wavelength**	**T, spec**	**T, meas**
F110W	311	850.0[a]	$1x10^{-4}$	$<2x10^{-6}$	1582.3[a]	$1x10^{-4}$	$<1x10^{-5}$
F125W	010	917.7	$1x10^{-4}$	$<2x10^{-5}$	1582.3	$1x10^{-4}$	$<6x10^{-6}$
F140W	001	1110.0	$1x10^{-4}$	$<1x10^{-4}$[b]	1690.0	$1x10^{-4}$	$<1x10^{-5}$

a. The original requirements document does not provide blue- and red-side wavelengths for the F110W OOB, due to the relatively late addition of this filter to the WFC3 filter set. The limits used to evaluate F110W are based upon the limits for F105W and F125W; the F110W filter easily meets these requirements (see plot in Appendix A).

b. The F140W blue side OOB is less than $1x10^{-4}$ except for a small region, ~750-820 nm, where the transmission rises to a maximum of nearly $1x10^{-3}$, shown in the OOB curve in Appendix A. The effect will be fully calibrated in upcoming ground tests.

Optical Characteristics

In addition to the WFC3 filter spectral requirements, there are also specifications as to the allowable focus shift, quality of the transmitted wavefront, acceptable wedge and ghost levels. A dedicated lab setup, simulating a WFC3-like beam, was built to test completed replacement filter candidates before installation into the IR filter wheel (Telfer 2007). Data were acquired via an InGaAs camera and analyzed using IRAF and IDL routines; details of the measurement setup and analysis procedures are available in the individual filter test reports as well as Baggett et al. (2006) and Telfer (2007). Table 3 presents the resulting as-built replacement filter performance for wavefront, focus, wedge and ghosting. The requirements for each of these parameters (as detailed in the CEI, SER OPT-015 and Boucarut 2003) can be summarized as follows.

Wavefront: The CEI specification states that no spectral element should displace the image on the detector by more than 0.2 pixels or degrade the image quality by more than 0.02 waves at 633nm. Transmitted wavefront over the 22mm diameter clear aperture is required to be 0.02 waves or less at 633nm.

Focus shift: The filters are required to be parfocal; the filters must provide a focal shift equivalent to 4mm +/- 0.1mm of fused silica at 1000nm.

Wedge: The specification indicates that no spectral element displace the image on the dector by more than 0.2 pixels. The maximum assembled filter wedge shall be less than 10 arc sec.

Filter ghosts: The CEI requirement calls for no more than 0.2% of the total light to fall within a discrete ghost. All of the IR filters, old and new, satisfy this specification.

Columns in Table 3

Filter name: identifier used in on-orbit and ground systems; part number is the same as that shown in the previous tables.

Wavefront error (rms, entire): rms wavefront error across the uncoated filter substrate, in waves at 633nm, as measured by the filter vendor.

Wavefront error (P/V, entire): peak-to-valley wavefront error across the uncoated filter substrate, in waves at 633nm, as measured by the filter vendor.

Wavefront error (rms, med): median of 3x3 grid of measurements (11mm diameter beam footprint) taken across the filter, in waves at 633nm.

Wavefront error (rms, max): maximum rms wavefront error of 3x3 grid of measurements (11mm diameter beam footprint) taken across the filter, in waves at 633nm.

Focus (avg): focal shift measured from phase retrieval data, in mm.

Focus (spec): focal shift specification, in mm.

Focus (error): difference between measured and required focus, in mm.

Shift: median PSF displacement over the filter, in units of WFC3 IR pixels.

Wedge: allowable wedge for the filter (must be 10 arc sec or less).

Ghost: amount of light falling into filter ghost, as a percent of the total point source light, measured in the lab with a 150W xenon arc lamp. Ghost strength can vary depending upon the source spectrum.

Table 3. Wavefront, focus, wedge, and ghost characteristics of the replacement filters.

filter name	part num	WF error (rms)	WF error (P/V)	WF error med rms[a]	WF error max rms[a]	focus (avg)	focus (spec)	focus error	shift (pix)	wedge (arc sec)	ghost (%)
F110W	311	0.019	0.09	0.0054	0.009	1.2781	1.2422	+0.0359	0.21	4.77	<0.1
F125W	010	0.021	0.10	0.0123	0.0422	1.2777	1.2422	+0.0355	0.13	3.10	<0.1
F140W	001	0.027	0.125	0.0146	0.0198	1.2636	1.2422	+0.0214	0.07	1.45	<0.1

a. Median rms and max rms wavefront errors measured using an 11mm diameter beam footprint.

Summary

Due to the acquisition of a new IR detector with significantly more quantum efficiency shortward of 800nm than in the previous detector, the F110W and F125W filters originally constructed on fused silica were remade on IR-transmitting colored glass. In addition, a filter no longer needed for IR channel alignment purposes (F093W) has been replaced by the scientifically-useful F140W. This report has presented the as-built properties of these replacement filters and is intended as an update to the report documenting the properties of the original IR filter set (Lupie et al. 2003).

Acknowledgements

The filter vendor, Barr Associates, and particularly George Allen, are thanked for their efforts in producing the best possible replacement filters for WFC3. Thanks are also due to the extended WFC3 team, at GSFC, STScI, and Ball, for input and advice during the process of filter procurement, characterization, and installation.

References

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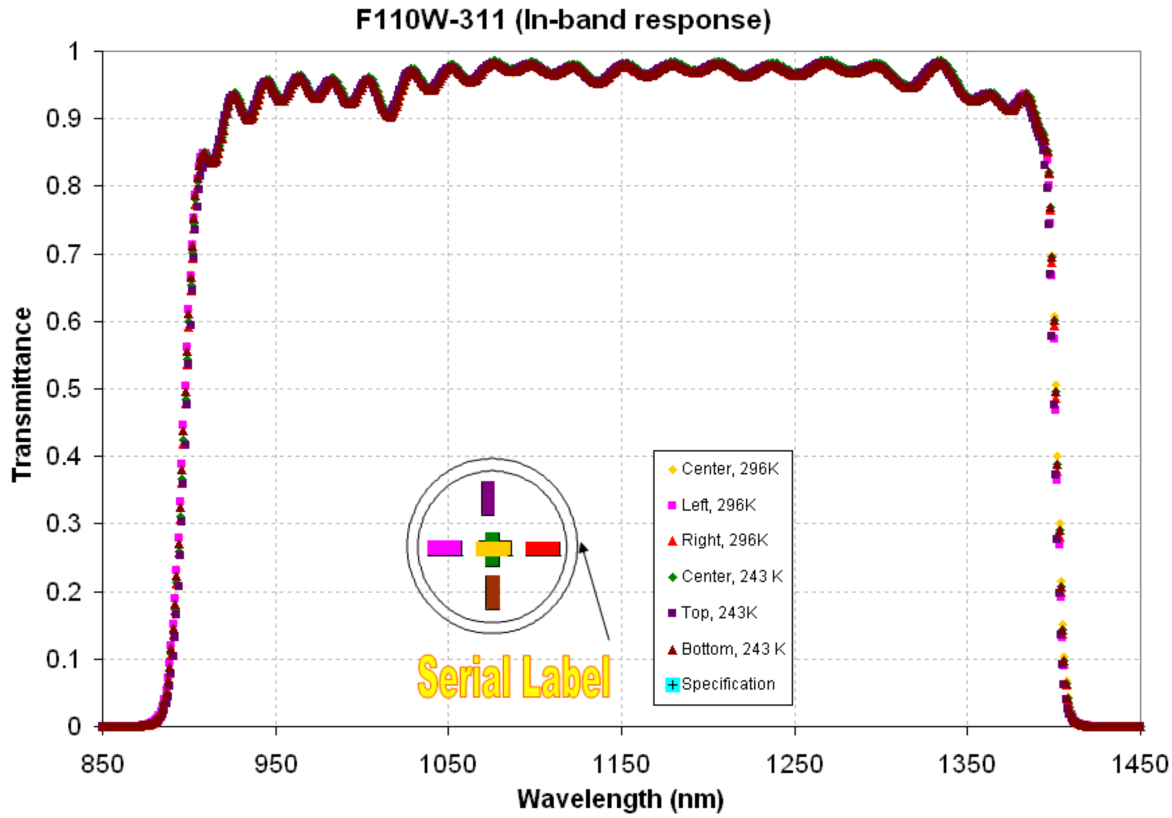
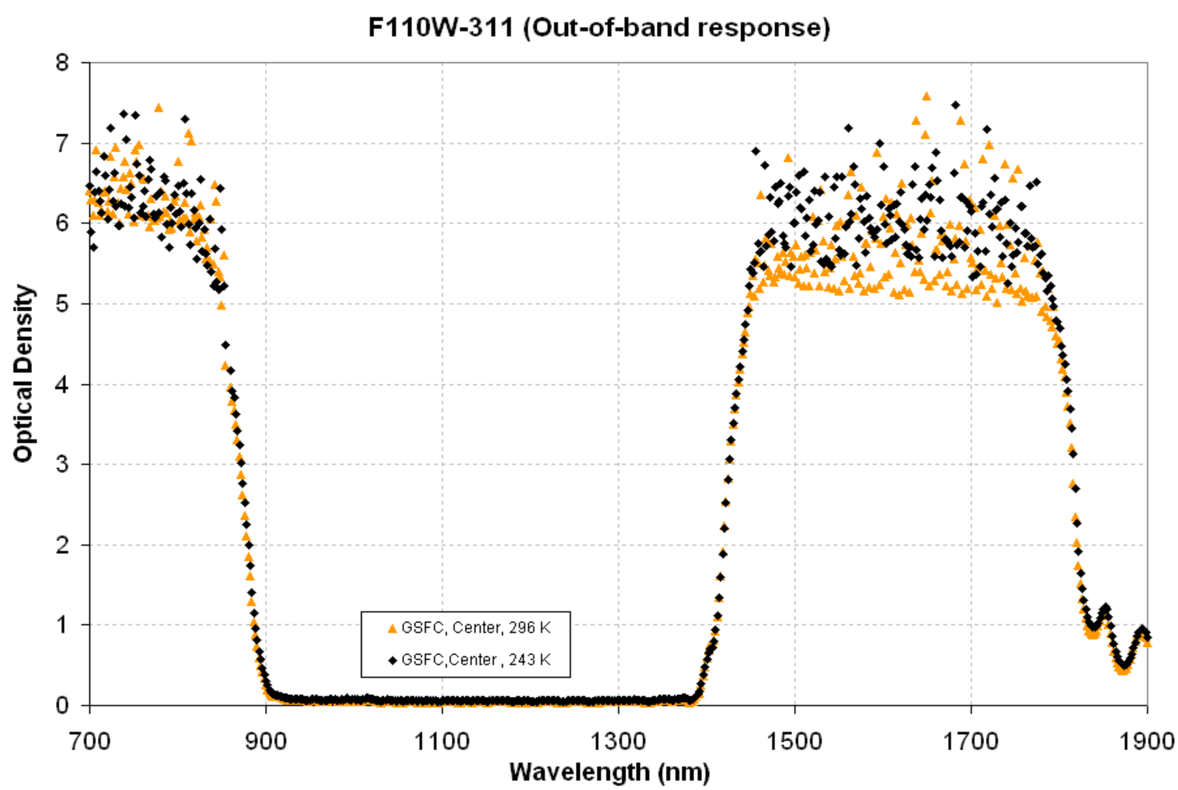
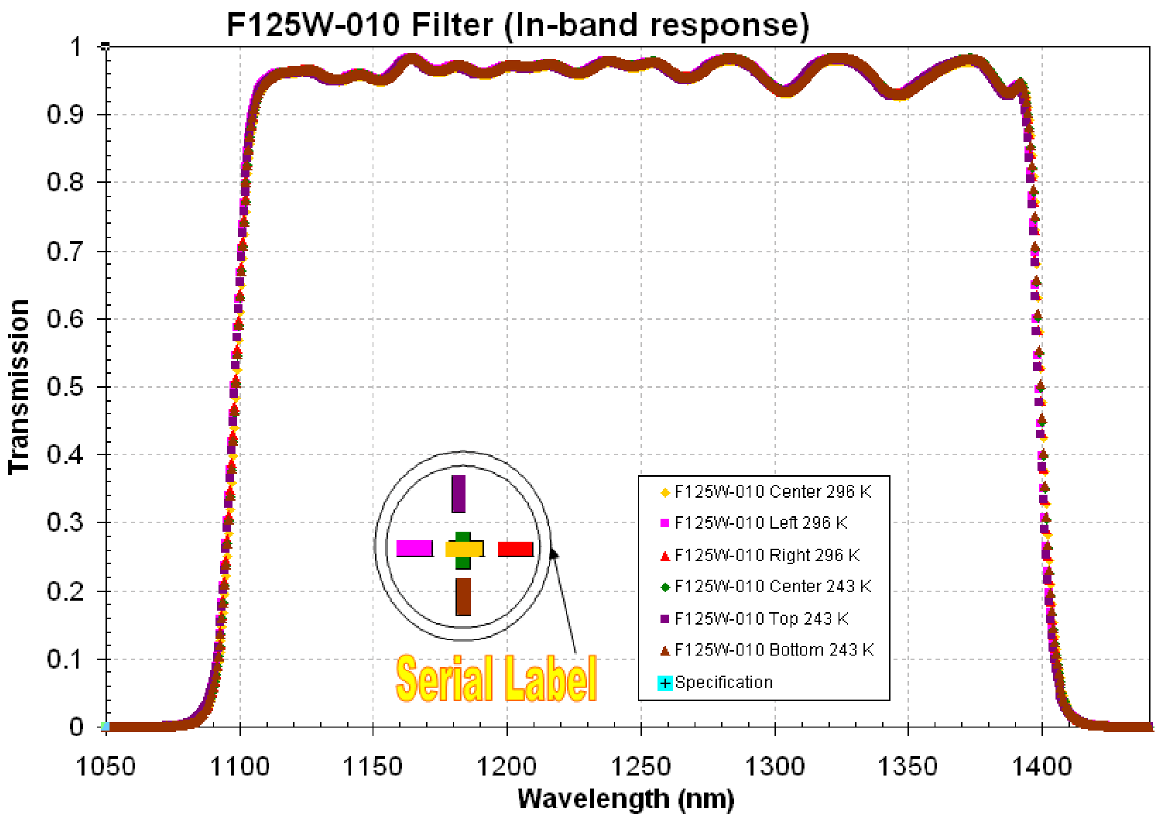
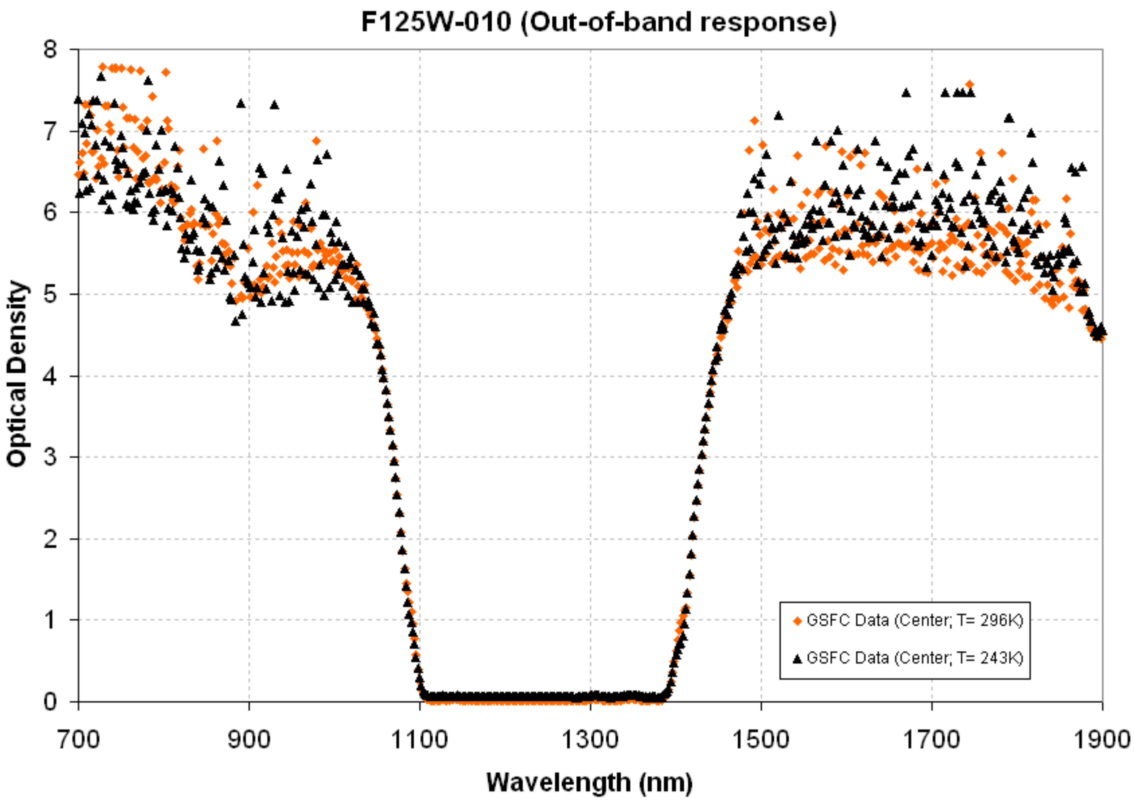
Appendix A.

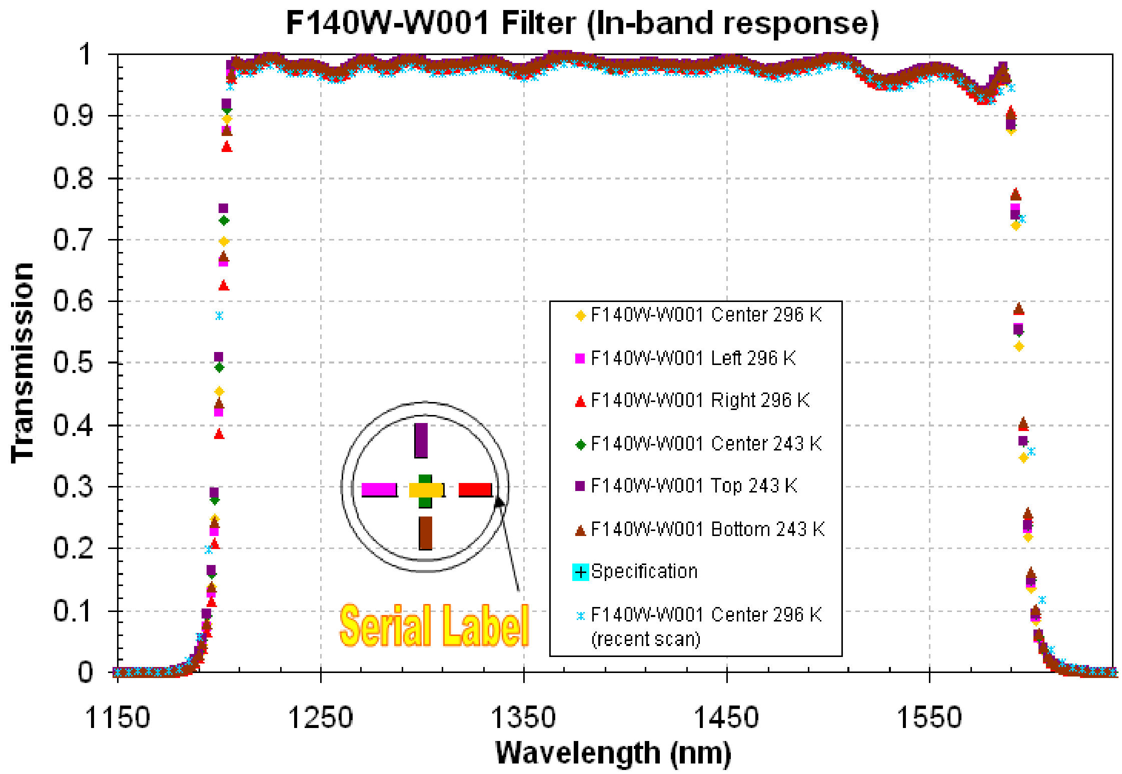
Figure 1: In-band and out-of-band (OOB) transmission scans for the replaced filters, the former on a scale of 0-1 and the latter in units of optical density (= -log10(transmission)). Filters were scanned at a variety of locations across the filter as noted in by the color-coding of the scans and the accompanying filter sketch, as well as at two temperatures (room temperature and operating temperture). A note about the OOB for F140W: the filter scans date from the original characterization of the filter performed in 2001. The GSFC data were limited by the sensitivity of the spectrometer available at the time (OD 3-4, see plot, dashed symbol) while the spectral scan from the vendor (Barr associates, diamond symbol) was obtained with a more sensitive instrument; the latter scan has been used for comparison with the requirements. A recent scan of the F140W witness piece, using the spectrophotometer currently available at GSFC (PE Lambda 950), shows excellent agreement with the prior Barr result. In addition, the witness scan confirms that the decrease in blocking between 700-800 nm seen in the original GSFC data is real; the effect will be calibrated in upcoming TV tests.


F110W-311 (In-band response)
Transmittance
Wavelength (nm)
Center, 296K
Left, 296K
Right, 296K
Center, 243 K
Top, 243K
Bottom, 243 K
Specification
Serial Label
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
850
950
1050
1150
1250
1350
1450

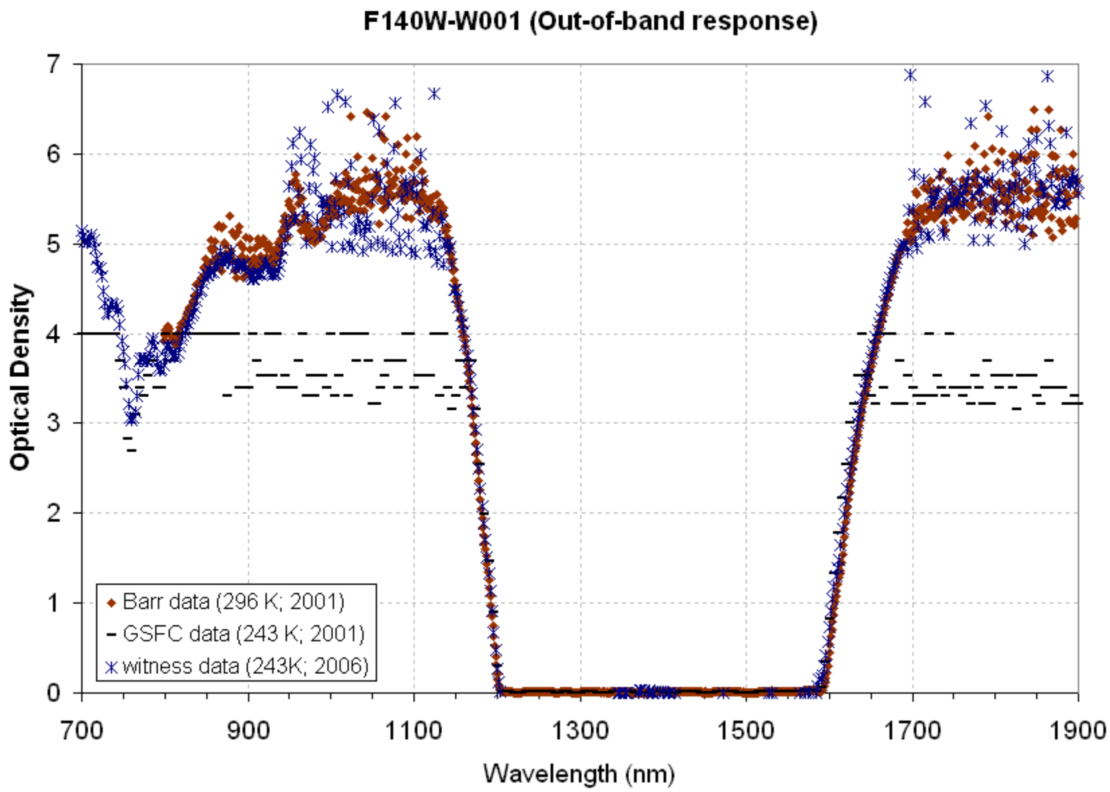

F110W-311 (Out-of-band response)
Optical Density
Wavelength (nm)
GSFC, Center, 296 K
GSFC,Center , 243 K
0
1
2
3
4
5
6
7
8
700
900
1100
1300
1500
1700
1900


F125W-010 Filter (In-band response)
Transmission
Wavelength (nm)
Serial Label
F125W-010 Center 296 K
F125W-010 Left 296 K
F125W-010 Right 296 K
F125W-010 Center 243 K
F125W-010 Top 243 K
F125W-010 Bottom 243 K
Specification


F125W-010 (Out-of-band response)
Optical Density
Wavelength (nm)
GSFC Data (Center; T= 296K)
GSFC Data (Center; T= 243K)



F140W-W001 Filter (In-band response)
Transmission
Wavelength (nm)
F140W-W001 Center 296 K
F140W-W001 Left 296 K
F140W-W001 Right 296 K
F140W-W001 Center 243 K
F140W-W001 Top 243 K
F140W-W001 Bottom 243 K
Specification
F140W-W001 Center 296 K (recent scan)
Serial Label



F140W-W001 (Out-of-band response)
Optical Density
Wavelength (nm)
Barr data (296 K; 2001)
GSFC data (243 K; 2001)
witness data (243K; 2006)