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Performance of the WFC3 Replacement UVIS Filters

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ABSTRACT

This report summarizes the performance of the dozen new filters procured for, and installed in, the WFC3 UVIS channel. The intent is to document the as-built properties of these new filters for future reference, providing an addendum to the original WFC3 report (Lupie & Boucarut, WFC3 ISR 2003-02) which presented the characteristics of the UVIS filter set in the instrument at that time.

Introduction

Images taken during initial instrument-level ground testing of WFC3 showed that while the majority of the 62 WFC3 UVIS filters satisfied the design specifications, a number of filters exhibited filter ghosts (Brown & Lupie 2004). Significant ghosting was found in three high science-priority UV filters - F218W, F225W, and F300X - at levels of ~10%, 15%, and 1%, respectively; the requirement specifies that <0.2% of the total incident light should fall within a discrete ghost. A number of other high, medium, and low science priority filters exhibited ghosts at the typically 0.5-1% level, though a few showed ghosts at 3-10%.

Subsequent ground-testing of the original spare filters in a lab setup specifically designed to mimic the WFC3 UVIS channel light beam showed that the ghosts were due to reflections between various filter coatings, results confirmed by surface modelling (Kubalak & Telfer 2005). The filter design dictates the type of ghost: an air-gap filter (two substrates joined by thin spacers) can generate complex extended ghosts which vary considerably across the field of view while a multi-substrate filter (stack of two or more substrates bonded together with optical adhesive) can generate more point-like ghosts with relatively minor variability across the field of view. In the UV filters (air-gap as well as single substrate designs), reflections from the metal blocker were found to be the primary cause of the observed ghosts. The filter vendors indicated that this type of coating is indeed the least controllable: the manufacturing process is such that the actual coating can deviate slightly from the original model design (particularly in the wings of the bandpass), which can give rise to filter ghosts.

In the case of multi-substrate filters, such as some of the visible medium-bands, the ghosts were found to be due to reflections arising from slight distortions in the adhesive layer used to bond this type of filter - a process made more difficult by the relatively large yet thin WFC3 filters. Due to their dimensions, WFC3 filters are less rigid than typical filters and therefore can exhibit slight “potato chipping”; such deviations in filter topography contribute to the observed ghost morphology (C. Grandy 2004). The complexity of the composite (coatings, substrates, epoxy bonding, topography) makes it very difficult to model or predict ghost behavior in multi-substrate filters; it can assessed only via lab measurements.

The WFC3 Science Oversight Committee (SOC) reviewed the filter ghost issue and provided recommendations as to which elements should be addressed with replacements, prioritized given the schedule and budget limitations at the time. As a result, new versions of more than a dozen high priority affected filters were made and fully characterized in the lab. Detailed evaluation and comparisons to the original flight filter characteristics showed that 10 of these new filters (plus a spare for each) were deemed acceptable as replacements. Thanks to advancements in filter coating technologies during the years since the original filters were designed, the new filters could be constructed on single substrates and in many cases, all bandpass-defining layers could be placed on one side of the substrate with an anti-reflection coat on the other side. The new designs significantly reduced the ghost levels, simplifying the ghost shapes and behavior across the field of view while maintaining, if not improving, other filter characteristics such as throughput or bandpass shape. The levels of filter ghosts in the majority of the final filter set are now <0.1%, easily satisfying the ghost requirement. A small number of filters still have ghosts exceeding the specification and are listed in Appendix A; they represent either the best overall effort of the vendors and/or were low enough science prority that replacements weren’t obtainable due to schedule constraints.

During the time period that the ghost problems were being addressed, two additional issues arose: inspections and testing of all original filters installed in the wheels revealed two filters with less than optimal edge beveling (F588N and F657N). Due to concerns about potential future edge chipping and as a consequence, possible risks to the SOFA mechanism (Sabatke 2006), these two filters were removed from the wheels and their edges re-worked to the specification. The filters were recharacterized to confirm, as expected, that the beveling had not changed their performance and they were successfully reinstalled. However, subsequent environmental testing revealed that one of the two filters (F588N) continued to have stability problems with its edges. With SOC approval, the F588N was replaced with F200LP, an alternative filter in-hand at the time (there was no viable spare for F588N).

Finally, due to a procedural error, one filter not intended for replacement (F600LP) was inadvertently removed from the filter wheel; its original flight spare was recharacterized, approved for flight, and installed into the wheel. Thus, in total 12 new filters were installed in the UVIS SOFA; they are tabulated in Table 1 (the table does not include F657N as that element is still the original flight filter). The remainder of this report is devoted to summarizing the primary performance characteristics of the new filters.

Table 1. Filters replaced in WFC3 UVIS filter wheels.

filter name	description	science priority	wheel	slot	filter name	description	science priority	wheel	slot
F200LP[a]	clear, grism reference	N/A	2	3	F410M	Stromgren v	medium	9	2
F218W	ISM feature	high	3	1	F467M	Stromgren b	medium	9	3
F225W	UV wide	high	3	2	F600LP	Long pass	high	6	3
F275W	UV wide	high	9	1	F606W	WFPC2 Wide V	high	6	2
F280N	Mg II 2795/2802	medium	4	2	F621M	11%	medium	8	3
F300X	extremely wide UV	high	1	2	F658N	[N II] 6583	medium	11	3

a. Replaced original F588N filter.

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 filters (Raouf & Trauger 2003) which included inspections and spectral scans as well as 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, and to check for anomalous flatfield features; the full set of characterization tests run on the 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 evaluated all candidate replacement filter test data for compliance with the filter requirements (JPL D-18189 requirements document, CEI specifications, and SER-OPT 015). Occasional compromises to the specifications were unavoidable given the practical limitations of the filter manufacturing process. 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. In some cases, such as UV filters which are notoriously difficult to manufacture, the specifications were understood to be meant as a challenge to the vendors, to push the envelope of current filter technology in order to obtain the best filter possible overall although it may require compromises in other areas (e.g., the replacement F218W has a ghost level of ~3.3%, down from ~10%, but the throughput - while still meeting the specification - is not as high as in the original air-gap filter). On the other hand, the new filter designs provided improvements in some of the replacement filters beyond simply mitigating the ghost problem, a welcome side-benefit (e.g., F225W ghosts were reduced from 15% to <0.3% while total throughput increased by 30% and F606W ghosts were reduced from 0.3% to 0.1% while total throughput increased by ~10%, and the passband became more square). On the other hand, not all new designs were completely successful: two replacement filters (F656N, F689M), while technically acceptable, were not significantly better than the original flight filters and as such, were not approved for use as replacements.

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 deviations of a filter from a particular specification were approved by the SOC given excellent performance characteristics in other areas.

The scans of the replacement filters chosen for flight are presented in Appendix B while Figure 1 and Table 2 below summarize the spectral results. These filters have now replaced their equivalent originals in the SOFA (except for F200LP, which as mentioned in the Introduction replaced F588N); as such, the properties listed in the tables here replace those listed in ISR 2003-02 (Lupie & Boucarut 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 (SYNPHOT) tables for use in the WFC3 calibration pipelines and into the web-based exposure time calculator (Brown 2006).

Table 2 presents the primary in-band 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 in units of nm, with a measurement accuracy +/- 0.5nm for the medium-band filters as well as F275W and F606W, +/- 0.1nm for the two narrowband filters, and +/-1nm for the remaining broad UV filters. In addition to the peak and edge transmission requirements, the specifications also called for a minimum of ripple within the 90% passband; that is, transmission within the 90% passband should not fall below 90%. Definitions of the spectral quantities shown in Table 2 originated in the JPL specification document (Trauger 2001), repeated here for convenience.

Table 3 presents the requirements for out-of-band (OOB) transmission longward of the passband along with the measured values of the replacement filters selected and approved for flight. Shortward of the passband, the specifications for wide- and medium-band filters required that the transmission be less than 10^{-6} at wavelengths shortward of λ_{-01} by a wavelength shift equal to the FWHM ($\lambda < \lambda_{-01} - \lambda_{+50} + \lambda_{-50}$). For narrow-band filters, the specifications called for the transmission to be less than 10^{-6} at all wavelengths shortward of the passband ($\lambda < 2x\lambda_{-01} - \lambda_{+01}$).

<u>Columns in Table 2 (in-band spectral scans)</u>
JPL filter number: general identification for filter within the entire UVIS set
Filter name: identifier used in on-orbit and ground systems.
Part Number: unique identifier of available candidates for a given filter; in the table, the part number identifies the specific replacement part ultimately chosen for flight.
λ_0 : the filter's central wavelength, given by = $[\lambda_{-50} \times \lambda_{+50}]^{1/2}$.
FWHM: full-width at the half-transmission points, is defined as ($[\lambda_{-50} - \lambda_{+50}]$.
λ_{-01} *and* λ_{+01} : wavelengths on either side of the central wavelength where the transmission is <1% absolute and remains below 1% for wavelengths shortward of λ_{-01} and longward of λ_{+01} .
λ_{-50} *and* 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 of λ_{-50} and longward of λ_{+50}.
λ_{-90} *and* λ_{+90} : wavelengths between which the transmission is greater than 90% absolute.
Min T: minimum average transmission averaged over the λ_{-90} and λ_{+90} range.
Comment: identifies row as design specification, measured values, or the difference.

Columns in Table 3 (out-of-band spectral scans)
JPL filter number: general identification for filter within the entire UVIS set
Filter name: identifier used in on-orbit and ground systems.
Part Number: unique identifier of available candidates for a given filter; in the table, the part number identifies the specific replacement part ultimately chosen for flight.
T_n: transmission specification at and longward of the wavelength λ_n.
λ_n: wavelength at which OOB T_n is specified.
Some filters have a single OOB requirement while others have a step-wise requirement of different levels at different wavelengths (denoted by subscript to T and λ).

Table 2. In-band throughput performance of the UVIS 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 '-'.

JPL Fnum	filter name	part num	λ_0	min T	FWHM	λ_{-50}	λ_{+50}	λ_{-90}	λ_{+90}	λ_{-01}	λ_{+01}	comment
	F200LP	312	-	-	-	<190.	-	194.6	-	-		meas; see A
UVIS-1	F218W	312	216.5	0.20	35.2	199.7	234.8	208.1	224.0	187.0	251.0	meas
			217.5	0.20	30.0	202.5	232.5	-	-	-	-	spec
			-1.0	0.00	+5.2	-2.8	+2.3	-	-	-	-	dev
UVIS-2	F225W	305	231.1	0.30	54.7	205.3	260.1	212.1	245.0	197.0	288.1	meas
			225.0	0.20	50.	200.0	250.0	-	-	-	-	spec
			-6.1	+0.10	+4.7	+5.3	+10.1	-	-	-	-	dev
UVIS-3	F275W	317	272.0	0.43	48.1	249.1	297.1	254.5	273.3	230.4	310.2	meas
			275.0	0.20	50.	250.	300.	-	-	-	-	spec
			-3.0	+0.23	-1.9	-0.9	-2.9	-	-	-	-	dev
UVIS-26	F280N	310	279.5	0.26	4.3	277.4	281.6	278.7	281.0	276.6	283.2	meas
			279.8	0.20	4.2	277.7	281.9	-	-	-	-	spec
			-0.3	+0.06	+0.1	-0.3	-0.3	-	-	-	-	dev
UVIS-15	F300X	312	274.3	0.49	75.3	239.2	314.5	244.3	284.7	216.4	401.5	meas
			-	0.50	-	-	365.0	-	-	-	-	spec; see B
			-	-0.01	-	-	-50.5	-	-	-	-	dev
UVIS-19	F410M	311	410.6	0.93	18.3	401.5	419.8	403.5	418.4	398.3	423.7	meas
			410.5	0.75	19.0	401.0	420.0	404.0	417.0	393.0	430.0	spec
			+0.1	+0.18	-0.7	+0.5	-0.2	-0.5	+1.4	+5.3	-6.3	dev
UVIS-20	F467M	311	468.2	0.88	21.8	457.4	479.2	458.0	478.0	454.5	482.9	meas

JPL Fnum	**filter name**	**part num**	λ_0	**min T**	**FWHM**	λ_{-50}	λ_{+50}	λ_{-90}	λ_{+90}	λ_{-01}	λ_{+01}	**comment**
			467.5	0.80	23.0	456.0	479.0	459.0	475.5	447.5	489.0	spec
			+0.7	+0.08	-1.2	+1.4	+0.2	-1.0	+2.5	+7.0	-6.1	dev
UVIS-17	F600LP	003	-	0.98	-	608.4	-	622.3	-	593.0	-	meas
			-	0.95	-	600.0	-	625.0	-	595.0	-	spec
			-	+0.03	-	+8.4	-	-2.7	-	-2.0	-	dev
UVIS-8	F606W	310	593.9	0.96	230.4	479.0	709.5	480.8	707.1	469.9	720.8	meas
			595.6	0.9	234.0	478.5	712.5	492.5	702.0	469.9	720.8	spec
			-1.7	+0.06	-3.6	+0.5	-3.0	-11.7	+5.1	0.0	0.0	dev
UVIS-22	F621M	311	621.1	0.95	63.1	590.4	653.5	593.5	650.2	494.9	661.7	meas
			621.2	0.85	64.0	590.0	654.0	-	-	-	-	spec
			-0.1	+0.10	-0.9	+0.4	-0.5	-	-	-	-	dev
UVIS-37	F658N	310	658.5	0.89	2.4	657.1	659.9	657.3	659.7	656.7	660.4	meas
			658.5	0.80	2.0	-	-	657.6	659.6	657.0	660.6	spec
			0.0	+0.09	+0.4	-	-	-0.3	+0.1	-0.3	-0.2	dev

Note A. No specific wavelength specifications exist for F200LP; it was constructed as a fused-silica element with an UV-optimized anti-reflection coat and has replaced UVIS-33 filter F588N.

Note B. The blue side of F300X was specified to be as short as filter technology would allow.

Table 3. Out-of-band throughput performance longward of the passband in the UVIS replacement flight filters; wavelengths are in nm. F200LP and F600LP are not included: the former was designed to have as much throughput as possible across the 200-1000nm range while in the latter, the blocking is provided by the color glass (RG610) specified to be used in the filter construction.

JPL Fnum	filter name	part num	λ	T, spec	T, meas	JPL Fnum	filter name	part num	λ	T, spec	T, meas
UVIS-1	F218W	312	275.	$1x10^{-3}$	$3.1x10^{-4}$	UVIS-26	F280N	310	400.	$1x10^{-4}$	$1.3x10^{-3}$
			325.	$1x10^{-4}$	$4.7x10^{-5}$				700.	$1x10^{-5}$	$1.2x10^{-5}$
			400.	$1x10^{-5}$	$9.4x10^{-5}$	UVIS-15	F300X	312	430.	$1x10^{-4}$	$1.7x10^{-3}$
UVIS-2	F225W	305	275.	$1x10^{-3}$	$4.4x10^{-2}$	UVIS-19	F410M	311	480.	$5 x 10^{-5}$	$5.9x10^{-6}$
			325.	$1x10^{-4}$	$3.0x10^{-4}$	UVIS-20	F467M	311	530.	$5 x 10^{-5}$	$1.6x10^{-6}$
			400.	$1x10^{-5}$	$1.9x10^{-5}$	UVIS-8	F606W	310	850.	$1x10^{-4}$	$2.6x10^{-5}$
UVIS-3	F275W	317	325.	$1x10^{-3}$	$9.9x10^{-5}$	UVIS-22	F621M	311	730.	$5 x 10^{-5}$	$3.4x10^{-6}$
			375.	$1x10^{-4}$	$4.7x10^{-6}$	UVIS-37	F658N	310	700.	$1x10^{-6}$	$2.4x10^{-6}$
			450.	$1x10^{-5}$	$2.3x10^{-5}$						

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 SOFA (Telfer 2006). Data were acquired via a CCD 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 in Baggett et al. (2006) and Telfer (2006). Table 4 presents the resulting as-built replacement filter performance for wavefront, focus, wedge and ghosting. The requirements for each of these parameters can be summarized as follows.

Wavefront: JPL requirements call for <1/4 and 1/2 wave peak-to-valley over the clear aperture in single-substrate and multi-substrate filters, respectively (from substrate drawing JPL 10195732). All replacement filters except for F600LP are single substrate which is a multi-substrate sandwich filter. The filter vendors measure the wavefront error over the entire filter clear aperture by means of an interferometer (columns 3,4 in Table 4); the wavefront error through the beam footprint (columns 5,6 in Table 4) was measured in the lab with the FilterGEISt setup. The peak to valley error over *individual* beam footprints are not listed in Table 4 as these are more restrictive than necessary to satisfy the CEI wavefront requirement, which calls for no more than 0.02 waves of transmitted wavefront error at 633nm.

Focus shift: The filters are required to be parfocal, that is, the focus shift of each filter (plus the two CCD windows) must equal the focus shift of a 5.500mm thick plano/plano fused silica substrate at a wavelength of 633nm plus the shift of two fused silica CCD windows.

Wedge: the CEI specifies a relative displacement limit: no more than 0.5 detector pixel shift. In the JPL requirements document, this is worded as no more than a 6×10^{-4} equivalent wedge across the 2.256 inch aperture.

Filter ghosts: CEI requirement calls for no more than 0.2% of the total light to fall within a discrete ghost. Though some replacement filters (e.g., F218W and F225W) still do not meet the ghost specification, overall, they were judged to be a significant improvement over the original flight filters and as such, have been approved by the SOC and installed in the SOFA.

<u>Columns in Table 4</u>

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

Part number: unique identifier of given filter.

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 9x9 grid of measurements (11mm diameter beam) taken across the filter, in waves at 633nm.

Wavefront error (rms, max): maximum rms wavefront error of 9x9 grid of measurements (11mm diameter beam) taken across the filter, in waves at 633nm.

Focus (avg): focal shift calculated 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 UVIS pixels.

Equivalent wedge: displacement in units of inches of wedge over the 2.256 inch aperture.

Ghost: amount of light falling into filter ghost, as 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 4. 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	WF error max rms	focus (avg)	focus (spec)	focus error	shift (pix)	equivalent wedge	ghost (%)
F200LP	312	-	-	0.0054	0.0132	1.4228	1.6979	-0.275	0.16	3.32×10^{-5}	0.35
F218W	312	0.034	0.18	0.0132	0.0328	1.2771	1.3662	-0.0891	0.43	7.74×10^{-5}	3.3
F225W	305	0.021	0.101	0.0117	0.0255	1.3678	1.3949	-0.0271	0.28	5.17×10^{-5}	0.3

filter name	part num	WF error (rms)	WF error (P/V)	WF error med rms	WF error max rms	focus (avg)	focus (spec)	focus error	shift (pix)	equivalent wedge	ghost (%)
F275W	317	0.036	0.163	0.0087	0.0169	1.4520	1.5297	-0.0777	0.20	3.82×10^{-5}	<0.1
F280N	310	0.024	0.15	0.0105	0.0229	1.4221	1.5388	-0.1167	0.26	5.08×10^{-5}	0.9
F300X	312	0.031	0.161	0.0146	0.0295	1.500	1.5200	-0.0200	0.27	5.13×10^{-5}	0.25
F410M	311	0.043	0.25	0.0085	0.0178	1.6744	1.6636	0.0108	0.11	2.35×10^{-5}	<0.1
F467M	311	0.029	0.17	0.0094	0.0251	1.6772	1.6876	-0.0104	0.36	7.61×10^{-5}	<0.1
F600LP	003	-	-	0.0131	0.0282	1.5892	1.7395	-0.1503	1.08	1.98×10^{-4}	<0.1
F606W	310	0.038	0.26	0.0125	0.0235	1.7012	1.7209	-0.0197	0.20	4.13×10^{-5}	<0.1
F621M	311	0.021	0.22	0.0072	0.0143	1.7405	1.7233	0.0172	0.19	4.09×10^{-5}	<0.1
F658N	310	0.041	0.21	0.0065	0.0217	1.6072	1.7287	-0.1215	0.23	4.97×10^{-5}	0.4

Summary

Due to filter ghost issues in a subset of the WFC3 UVIS filters, some of the original filters have been replaced with improved versions. The as-built properties of these replacement filters have been presented along with the filter requirements. The results summarized here are intended as an update to the report documenting the original UVIS filter set (Lupie & Boucarut 2003).

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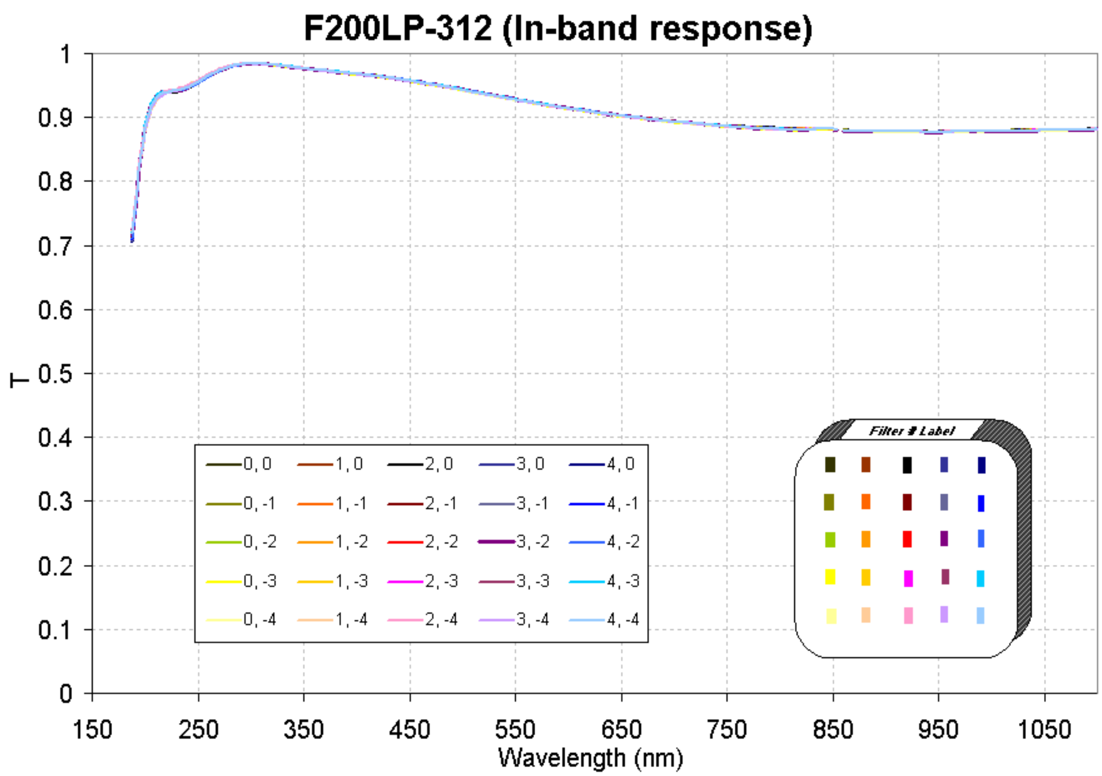
Appendix A

Table 5. Filters currently in WFC3 which do not meet the filter ghost requirement (<0.2% of the total flux in a ghost). Ghost levels in unasterisked filters (replacement filters) were measured from data taken in a lab setting and should be representative of what will be seen during upcoming instrument level tests. Ghost levels for asterisked filters were measured from data taken during prior instrument-level tests (Brown & Lupie 2004). The asterisked filters were *not* replaced, due either to their low science priority or because the acquired replacement candidates were not significantly better than the original flight filter or because the ghost level was deemed acceptable in light of the otherwise excellent performance characteristics of the filter.

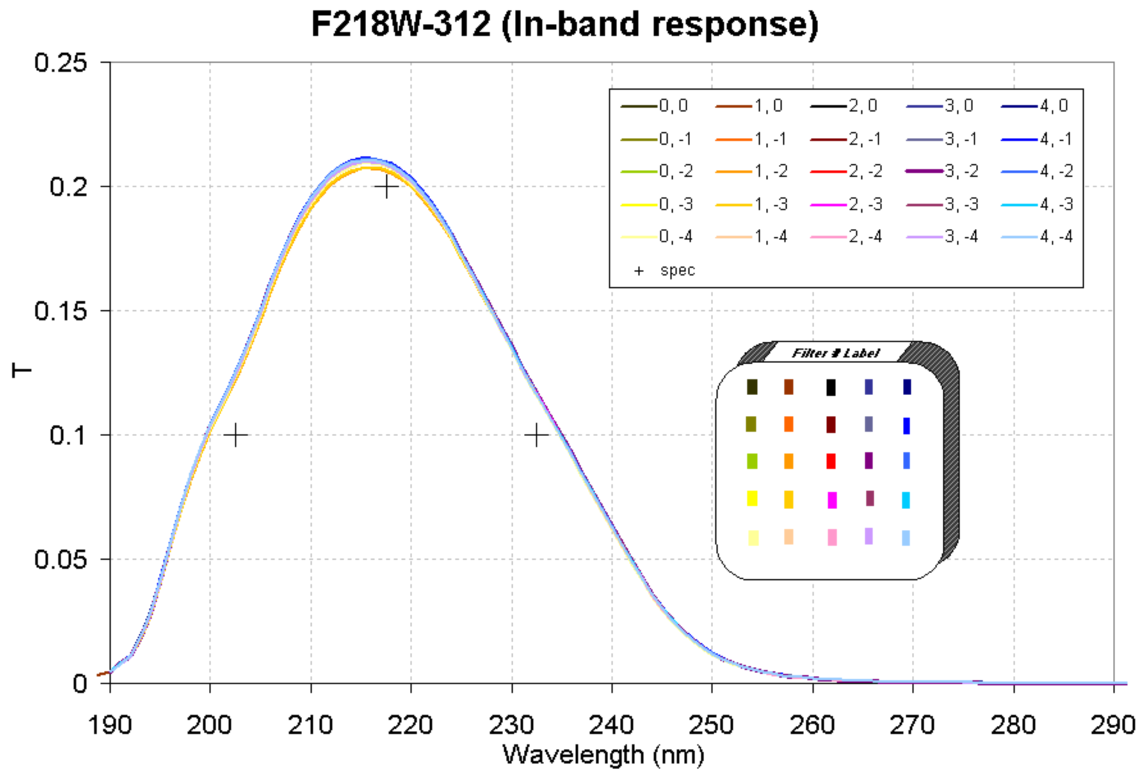
filter	description	ghost level (in percent)	science priority	filter	description	ghost level (in percent)	science priority
F200LP	Clear, grism reference	0.35	N/A	F218W	ISM feature	3.3	high
F225W	UV wide	0.3	high	FQ232N*	CII] 2326	5.0	low
FQ243N*	[Ne IV] 2425	5.0	low	F280N	Mg II 2795/2802	0.9	medium
F300X	Extremely wide UV	0.25	high	F656N*	Hα 6562	0.5	high
F658N	[N II] 6583	0.4	medium	F665N*	z(Hα + [N II])	0.4	low
F673N*	[S II] 6717/6731	0.3	medium	F680N*	z(Hα + [NII])	0.3	low

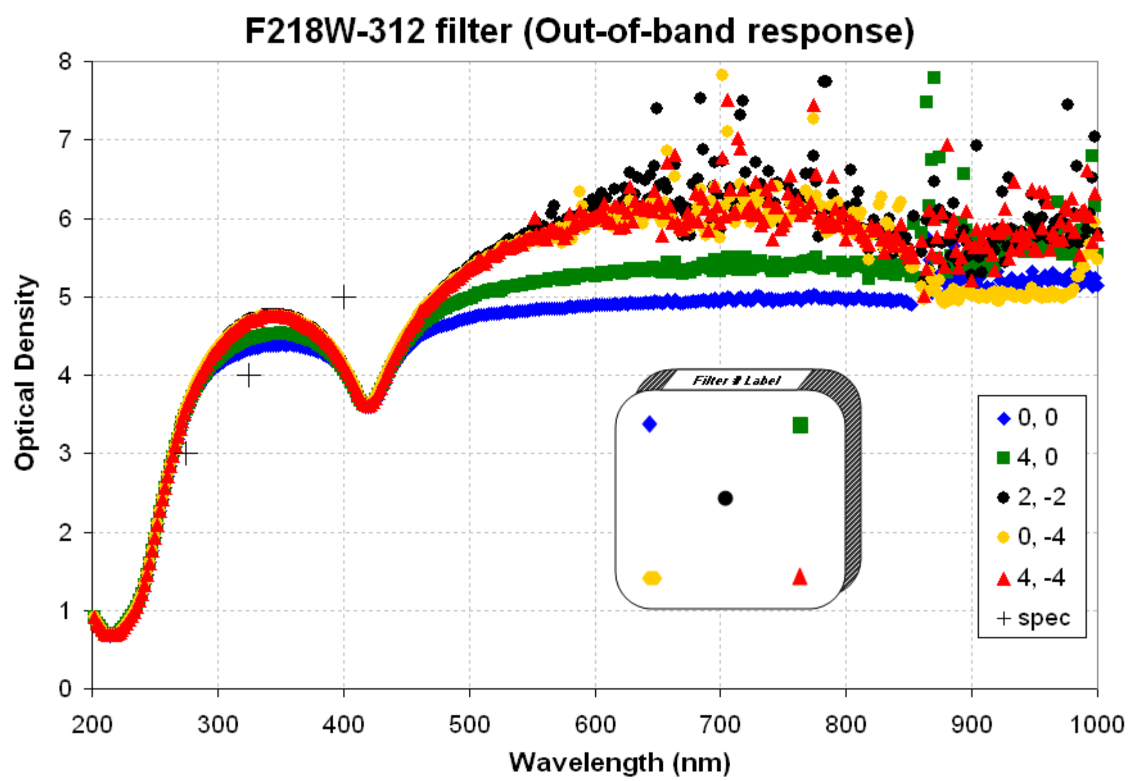
Appendix B

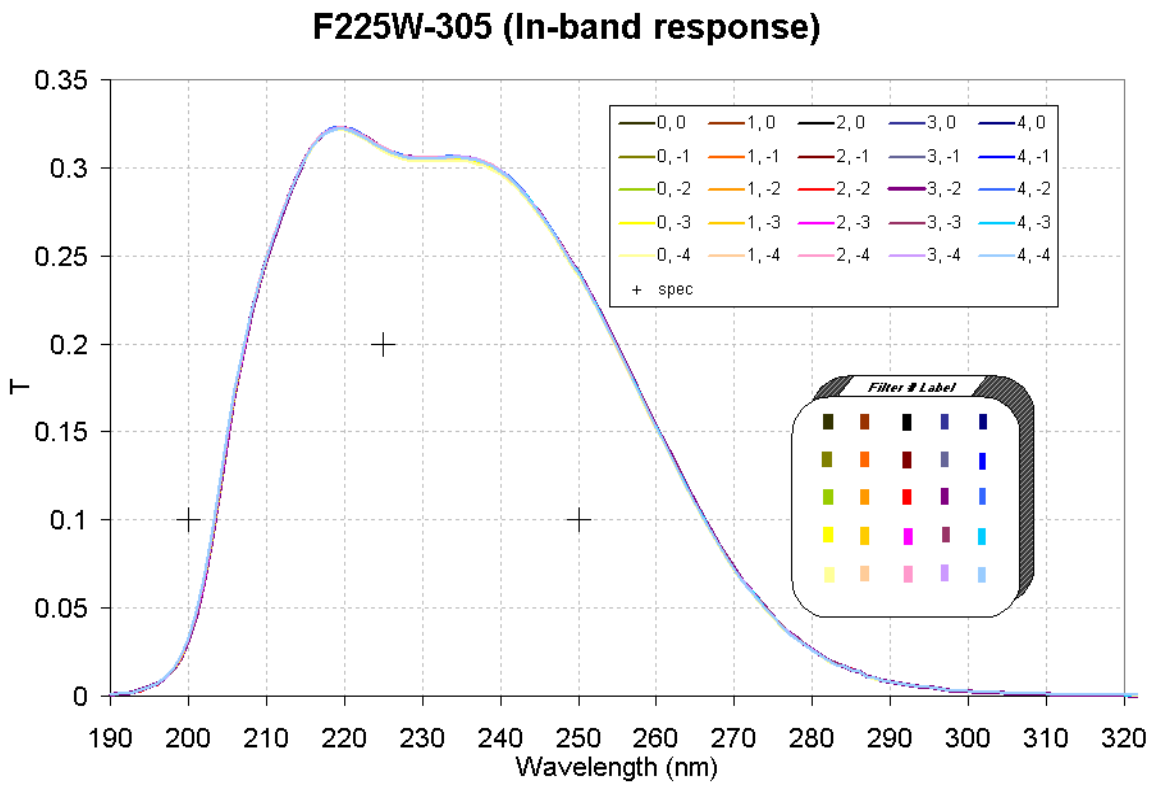
Figure 1: In-band and out-of-band (OOB) transmission scans for the replaced filters, the former on a scale of 0-1 and the latter in units of optical density (= -log10(transmission)). Filters were scanned in a variety of locations across the filter (as noted in by the color-coding of the scans and the associated filter sketch). For some filters, there is a slight discontinuity in the OOB scan between 800-900 nm; the jump is not real but an instrumental artifact due to a change in the spectrophotometer detectors in this region. The optical density measurements beyond this feature represent lower limits, that is, the blocking is better than the measurements indicate.

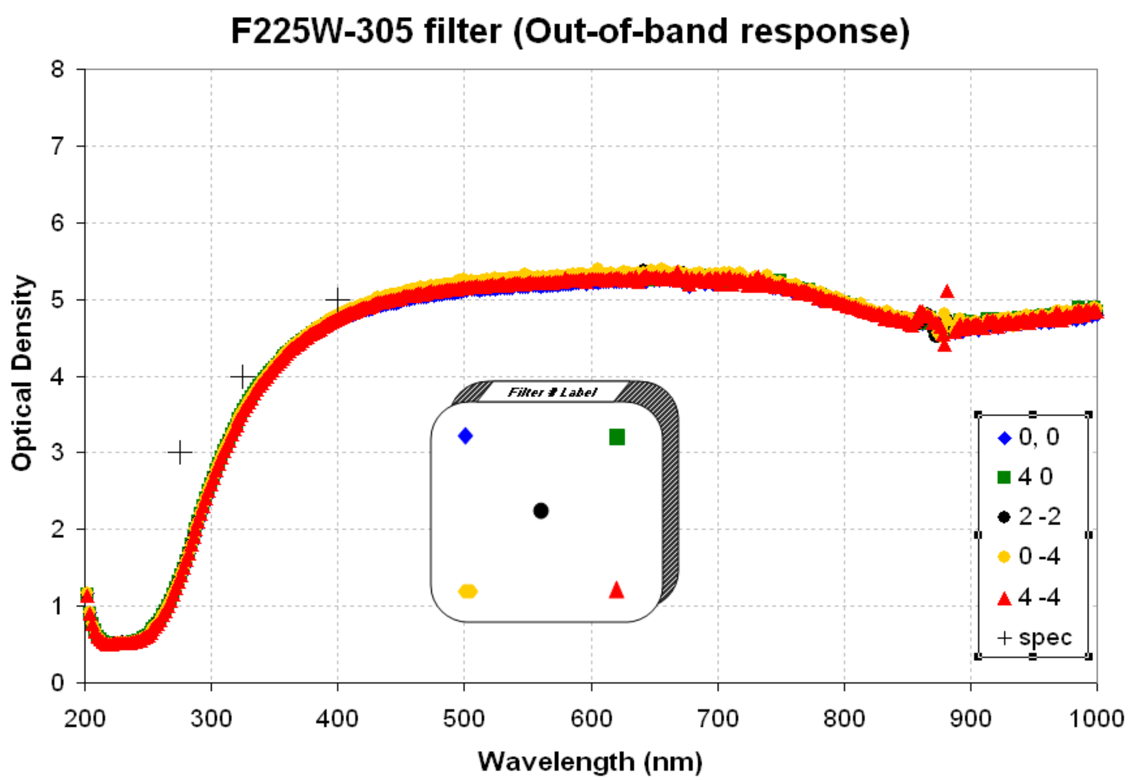


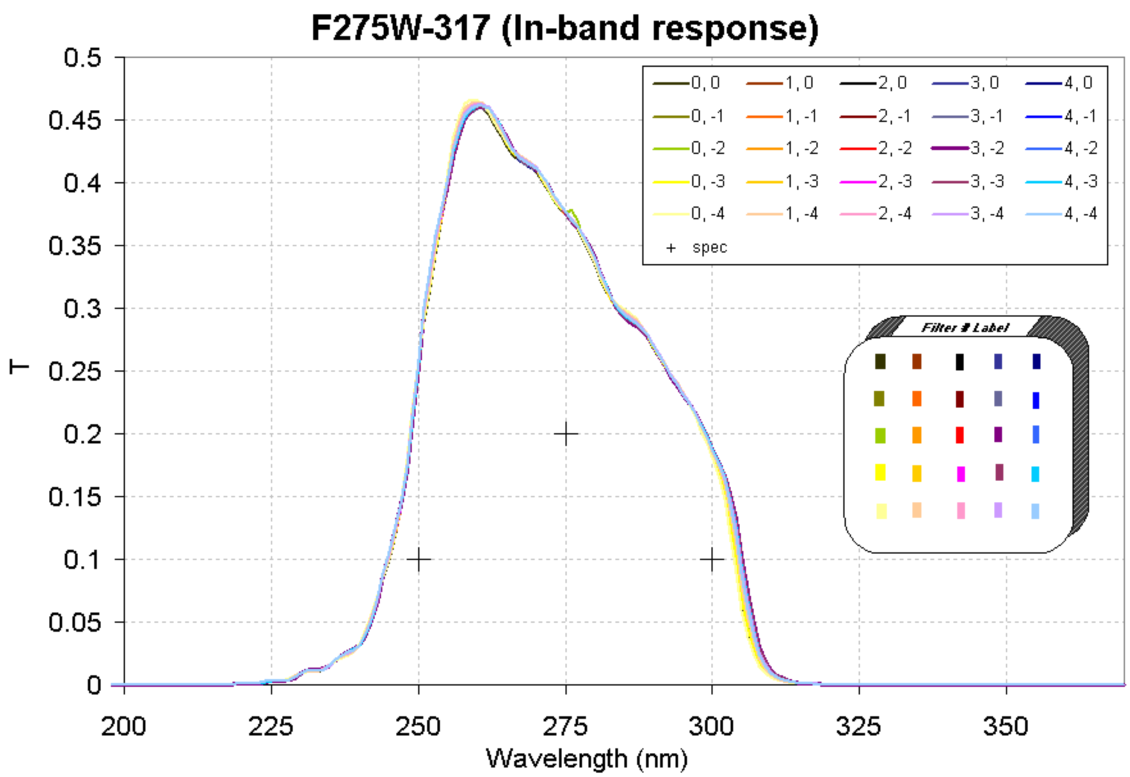
No OOB for F200LP.

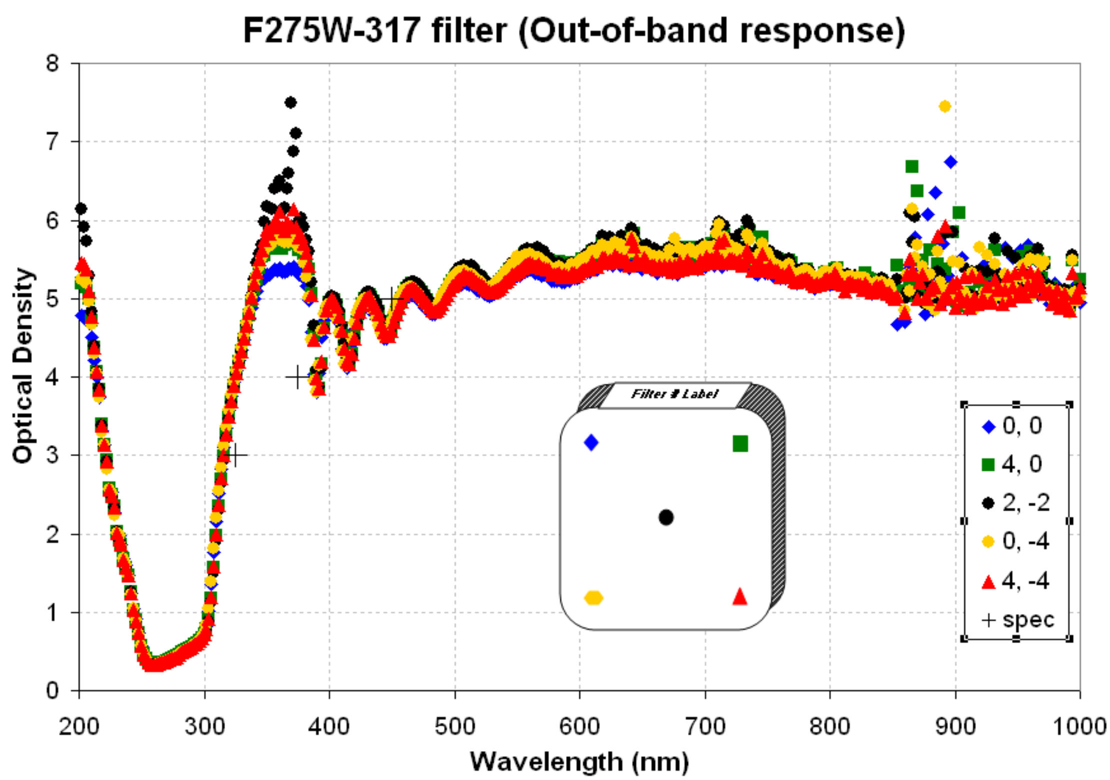

F218W-312 (In-band response)
T
Wavelength (nm)
0, 0
1, 0
2, 0
3, 0
4, 0
0, -1
1, -1
2, -1
3, -1
4, -1
0, -2
1, -2
2, -2
3, -2
4, -2
0, -3
1, -3
2, -3
3, -3
4, -3
0, -4
1, -4
2, -4
3, -4
4, -4
spec
Filter # Label

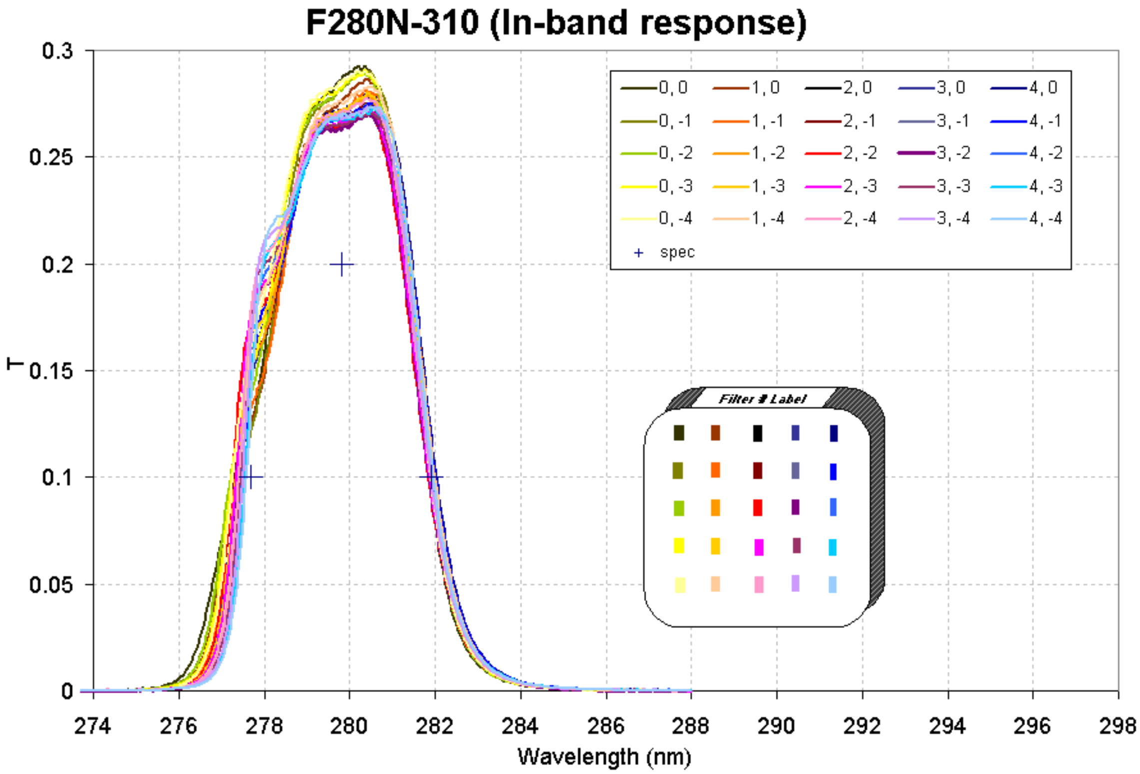

F218W-312 filter (Out-of-band response)
Optical Density
Wavelength (nm)
Filter # Label
0, 0
4, 0
2, -2
0, -4
4, -4
spec

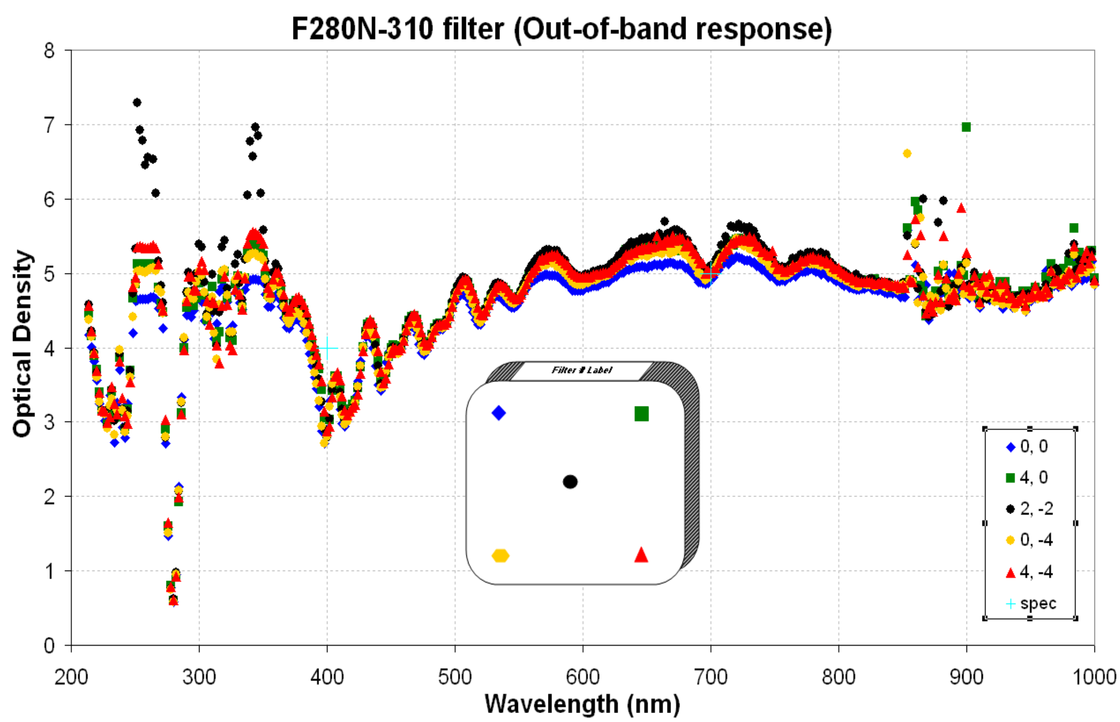

F225W-305 (In-band response)
T
Wavelength (nm)
0, 0
1, 0
2, 0
3, 0
4, 0
0, -1
1, -1
2, -1
3, -1
4, -1
0, -2
1, -2
2, -2
3, -2
4, -2
0, -3
1, -3
2, -3
3, -3
4, -3
0, -4
1, -4
2, -4
3, -4
4, -4
spec
Filter # Label

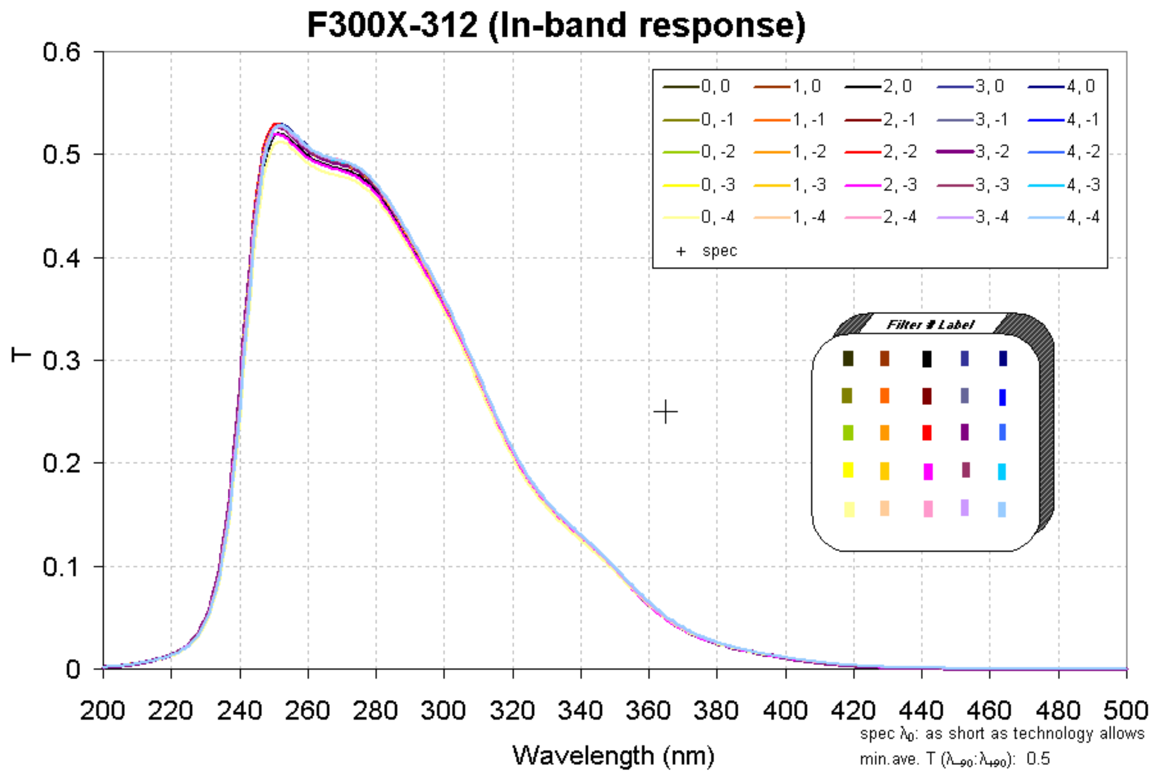

F225W-305 filter (Out-of-band response)
Optical Density
Wavelength (nm)
0, 0
4 0
2 -2
0 -4
4 -4
spec
Filter # Label

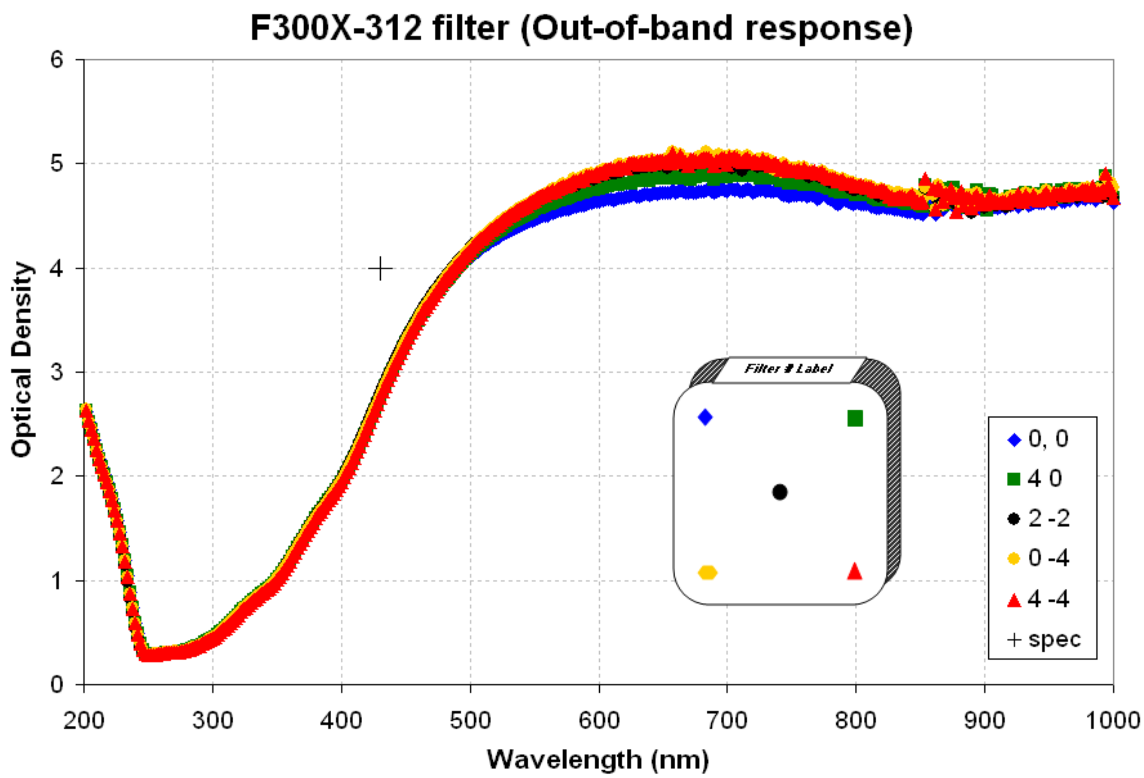

F275W-317 (In-band response)
T
Wavelength (nm)
0, 0
1, 0
2, 0
3, 0
4, 0
0, -1
1, -1
2, -1
3, -1
4, -1
0, -2
1, -2
2, -2
3, -2
4, -2
0, -3
1, -3
2, -3
3, -3
4, -3
0, -4
1, -4
2, -4
3, -4
4, -4
spec
Filter # Label

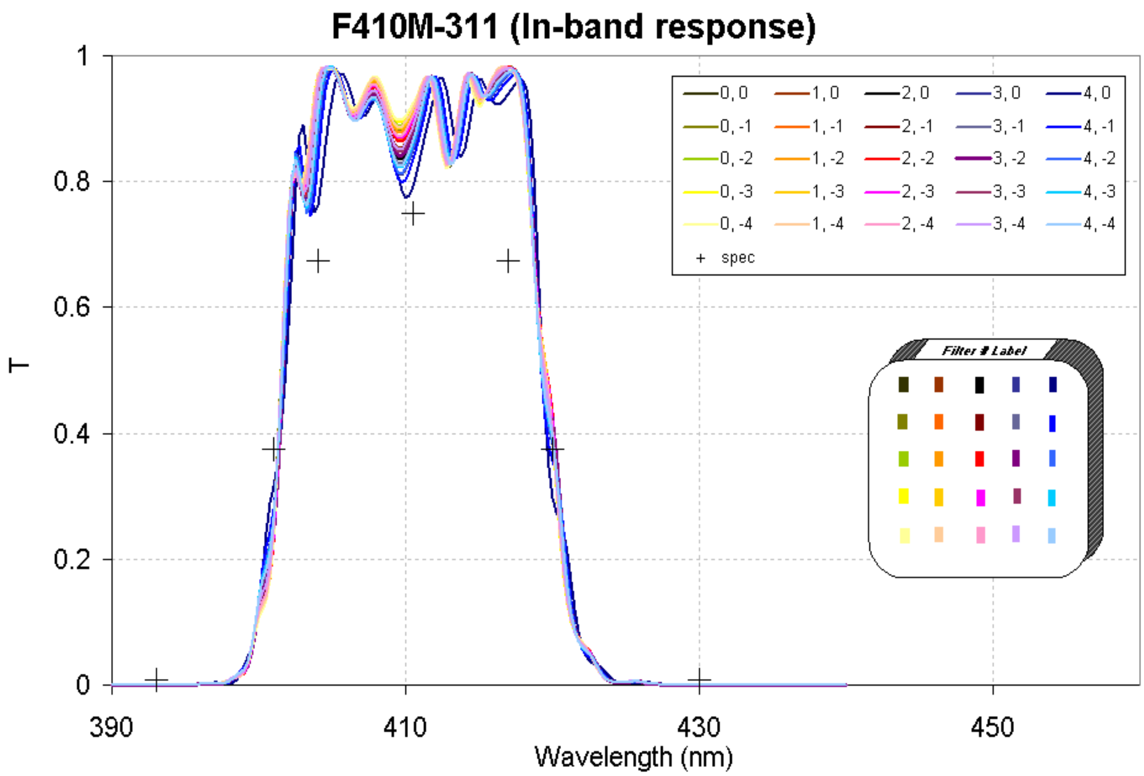

F275W-317 filter (Out-of-band response)
Optical Density
Wavelength (nm)
0, 0
4, 0
2, -2
0, -4
4, -4
spec
Filter # Label

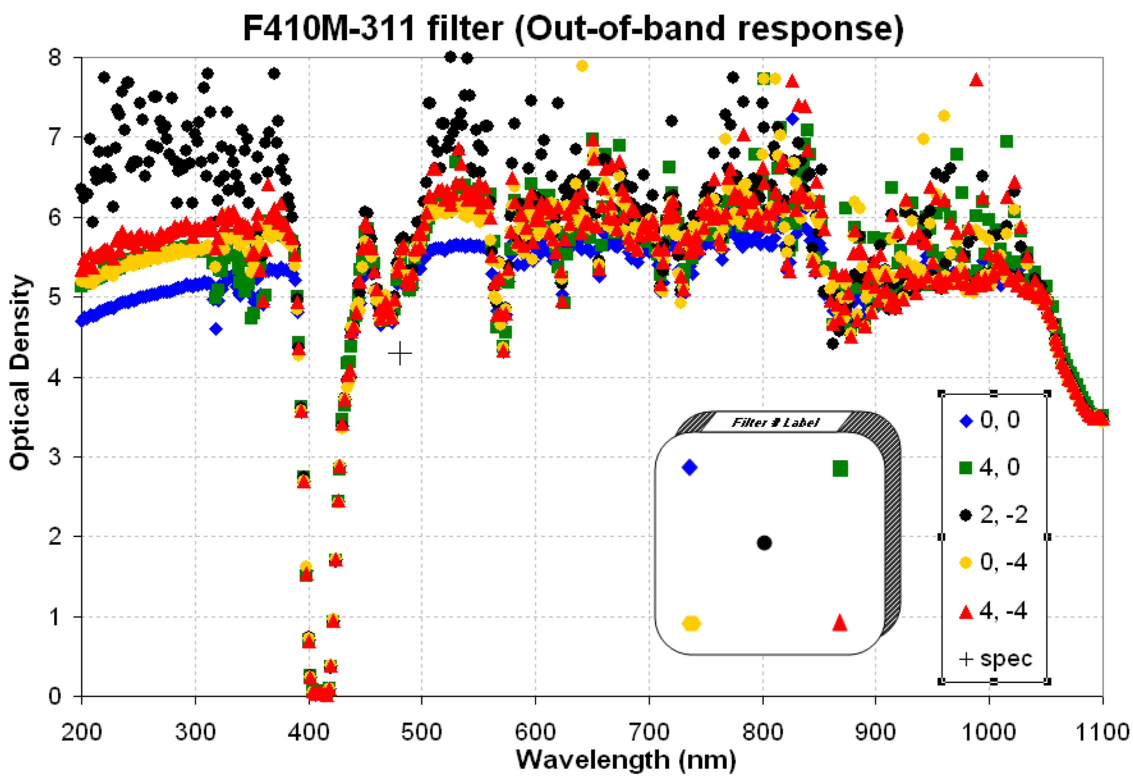

F280N-310 (In-band response)
0.3
0.25
0.2
T 0.15
0.1
0.05
0
274
276
278
280
282
284
286
288
290
292
294
296
298
Wavelength (nm)
0, 0
1, 0
2, 0
3, 0
4, 0
0, -1
1, -1
2, -1
3, -1
4, -1
0, -2
1, -2
2, -2
3, -2
4, -2
0, -3
1, -3
2, -3
3, -3
4, -3
0, -4
1, -4
2, -4
3, -4
4, -4
spec
Filter # Label

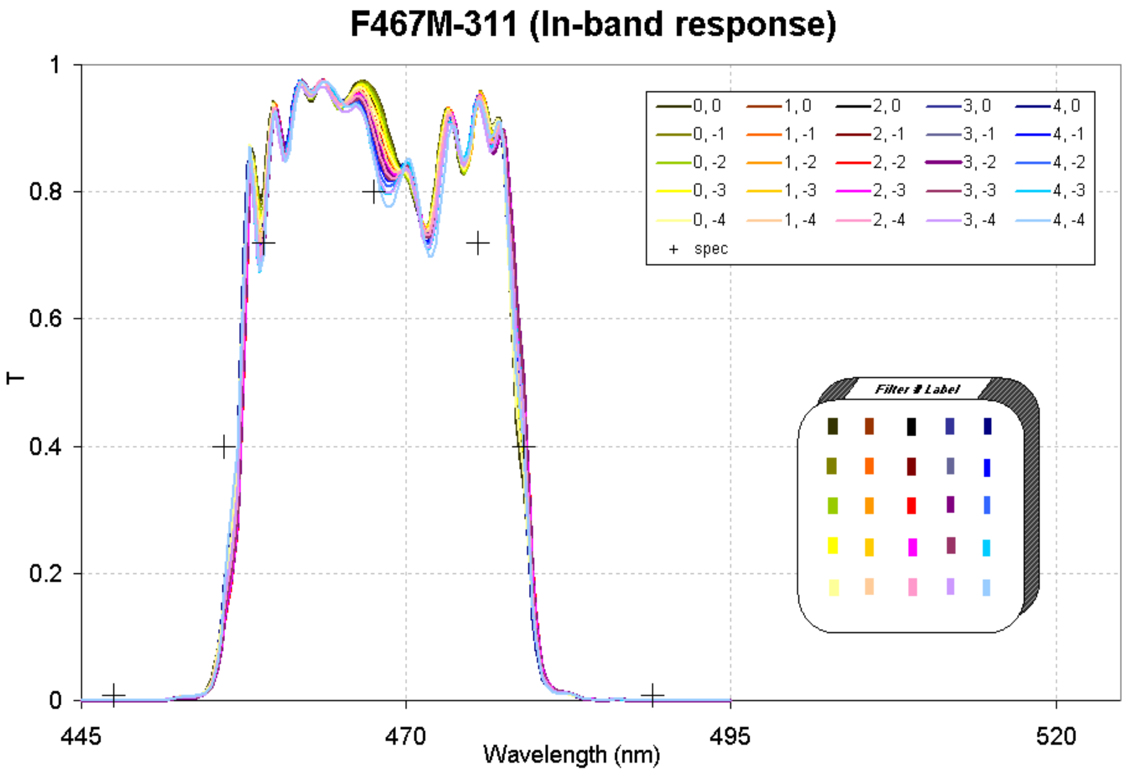

F280N-310 filter (Out-of-band response)
8
7
6
5
4
3
2
1
0
Optical Density
200
300
400
500
600
700
800
900
1000
Wavelength (nm)
Filter # Label
0, 0
4, 0
2, -2
0, -4
4, -4
spec

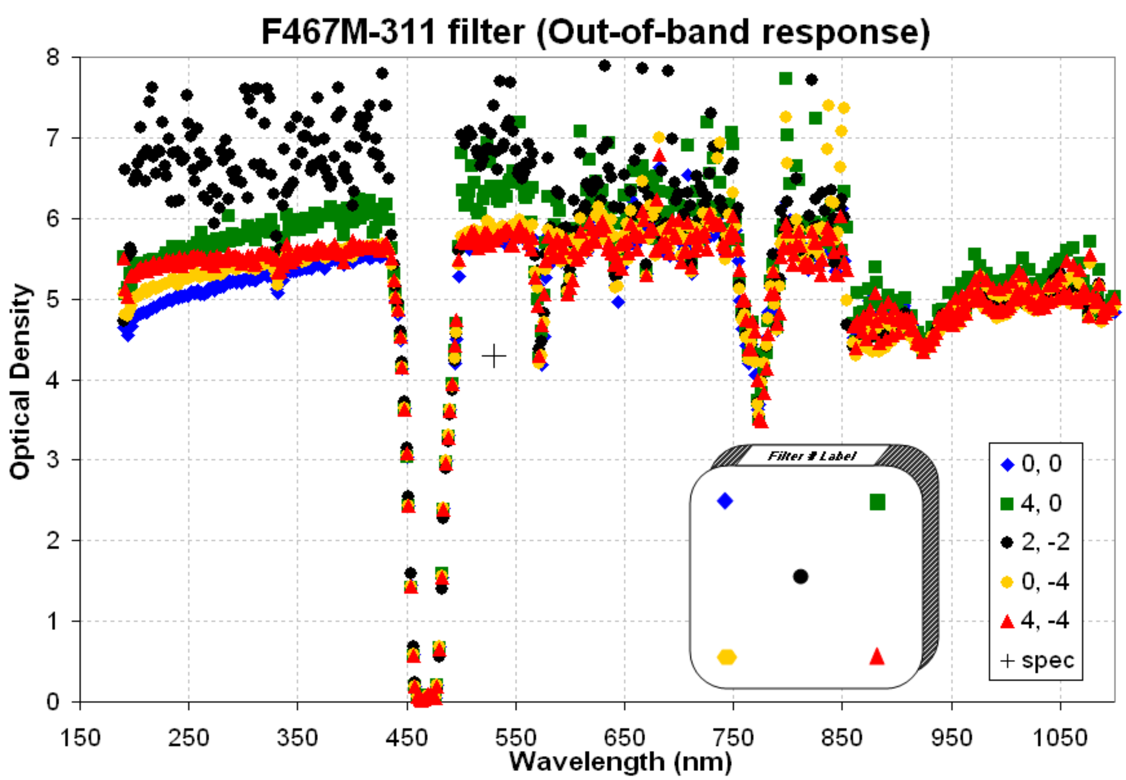

F300X-312 (In-band response)
T
Wavelength (nm)
0, 0
1, 0
2, 0
3, 0
4, 0
0, -1
1, -1
2, -1
3, -1
4, -1
0, -2
1, -2
2, -2
3, -2
4, -2
0, -3
1, -3
2, -3
3, -3
4, -3
0, -4
1, -4
2, -4
3, -4
4, -4
+ spec
Filter # Label
spec λ0: as short as technology allows
min.ave. T (λ-90:λ+90): 0.5

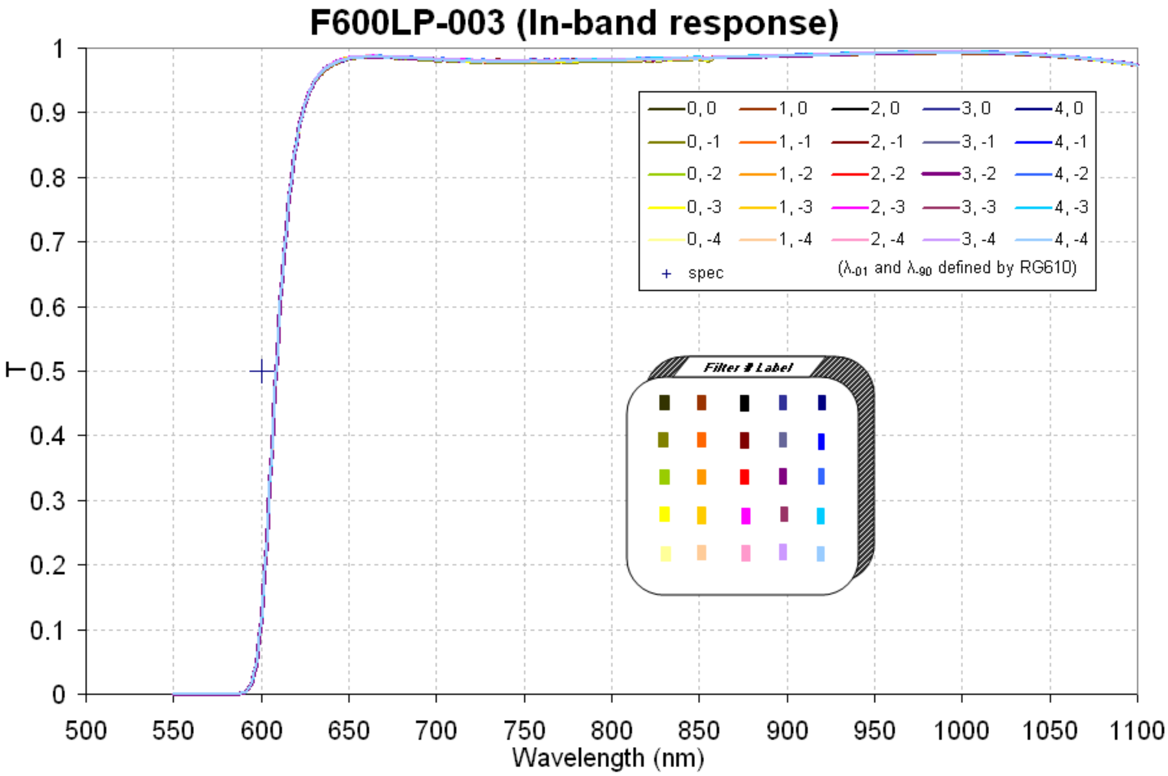

F300X-312 filter (Out-of-band response)
Optical Density
Wavelength (nm)
Filter # Label
0, 0
4 0
2 -2
0 -4
4 -4
+ spec

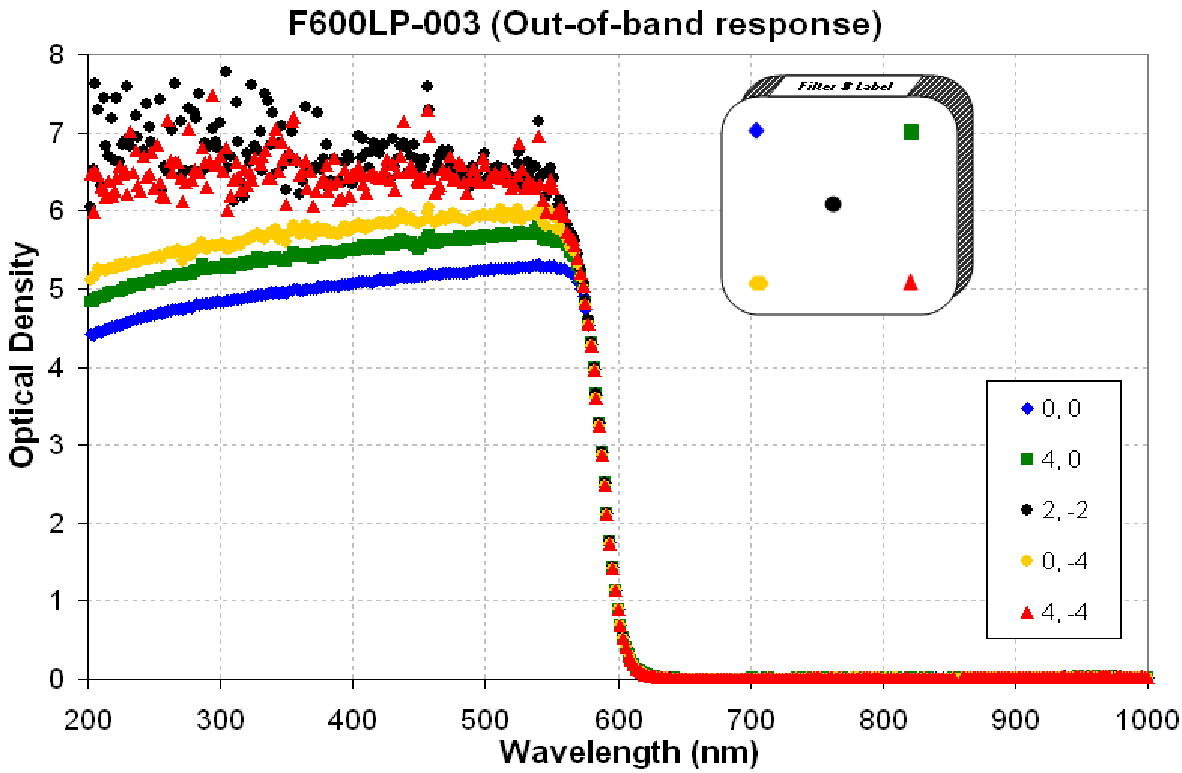

F410M-311 (In-band response)
T
Wavelength (nm)
0,0
1,0
2,0
3,0
4,0
0,-1
1,-1
2,-1
3,-1
4,-1
0,-2
1,-2
2,-2
3,-2
4,-2
0,-3
1,-3
2,-3
3,-3
4,-3
0,-4
1,-4
2,-4
3,-4
4,-4
+ spec
Filter # Label

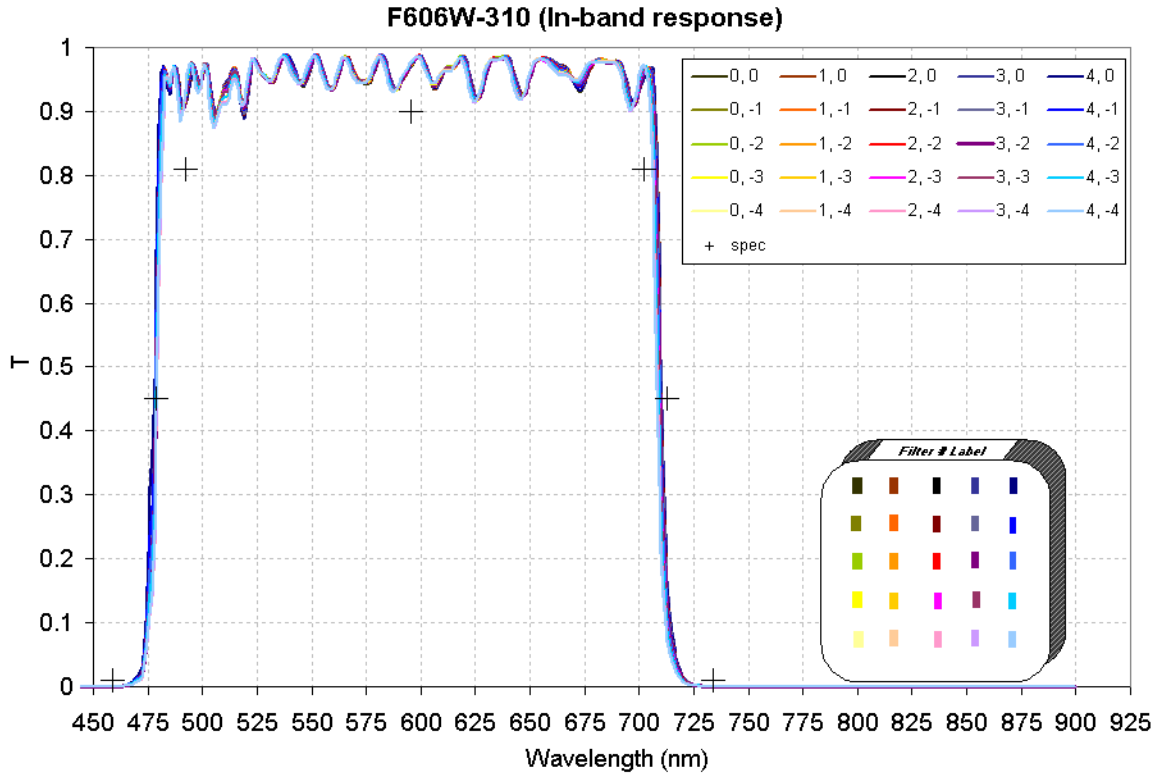

F410M-311 filter (Out-of-band response)
Optical Density
Wavelength (nm)
Filter # Label
0, 0
4, 0
2, -2
0, -4
4, -4
+ spec

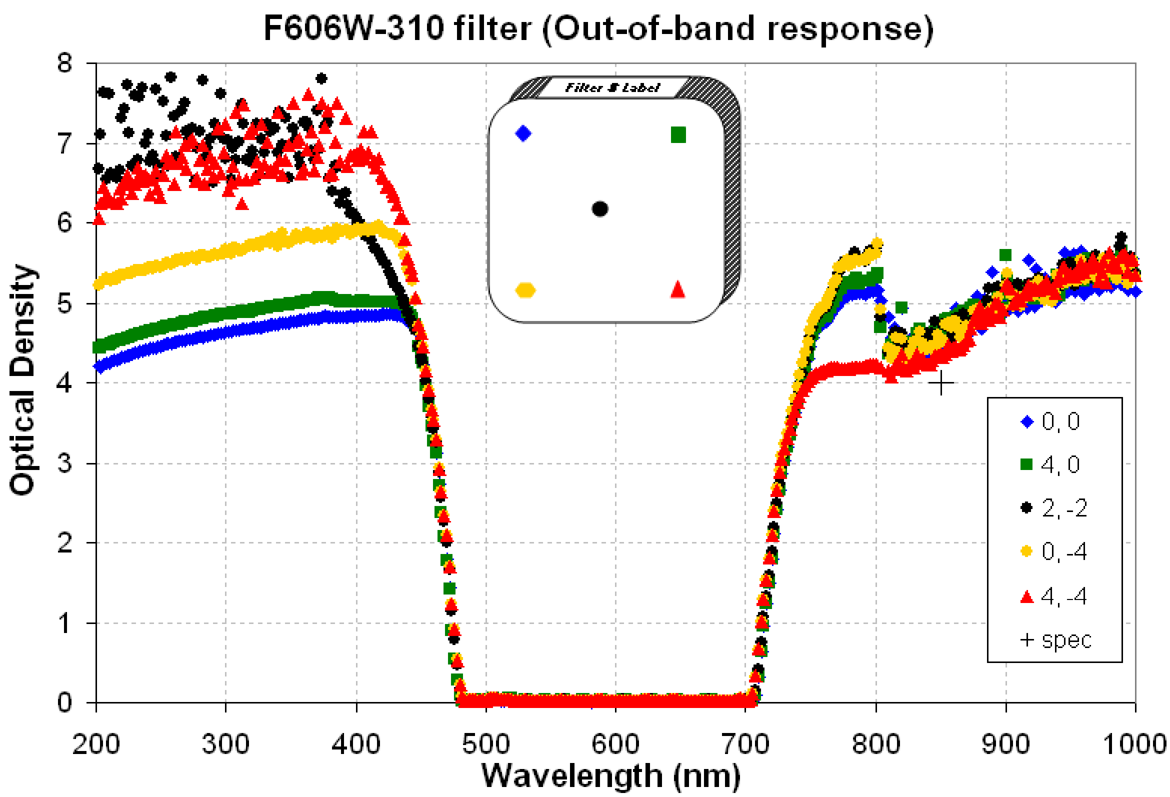

F467M-311 (In-band response)
T
Wavelength (nm)
445
470
495
520
0
0.2
0.4
0.6
0.8
1
0, 0
0, -1
0, -2
0, -3
0, -4
1, 0
1, -1
1, -2
1, -3
1, -4
2, 0
2, -1
2, -2
2, -3
2, -4
3, 0
3, -1
3, -2
3, -3
3, -4
4, 0
4, -1
4, -2
4, -3
4, -4
spec
Filter # Label

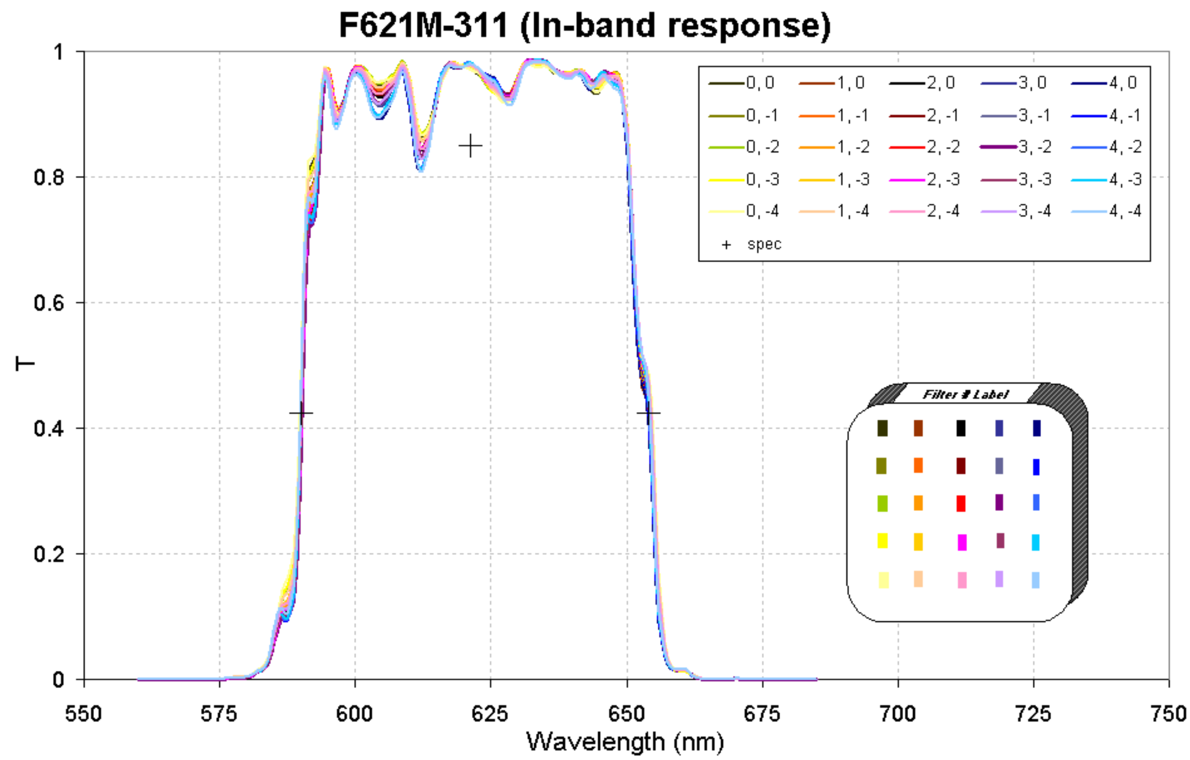

F467M-311 filter (Out-of-band response)
Optical Density
Wavelength (nm)
150
250
350
450
550
650
750
850
950
1050
0
1
2
3
4
5
6
7
8
0, 0
4, 0
2, -2
0, -4
4, -4
spec
Filter # Label

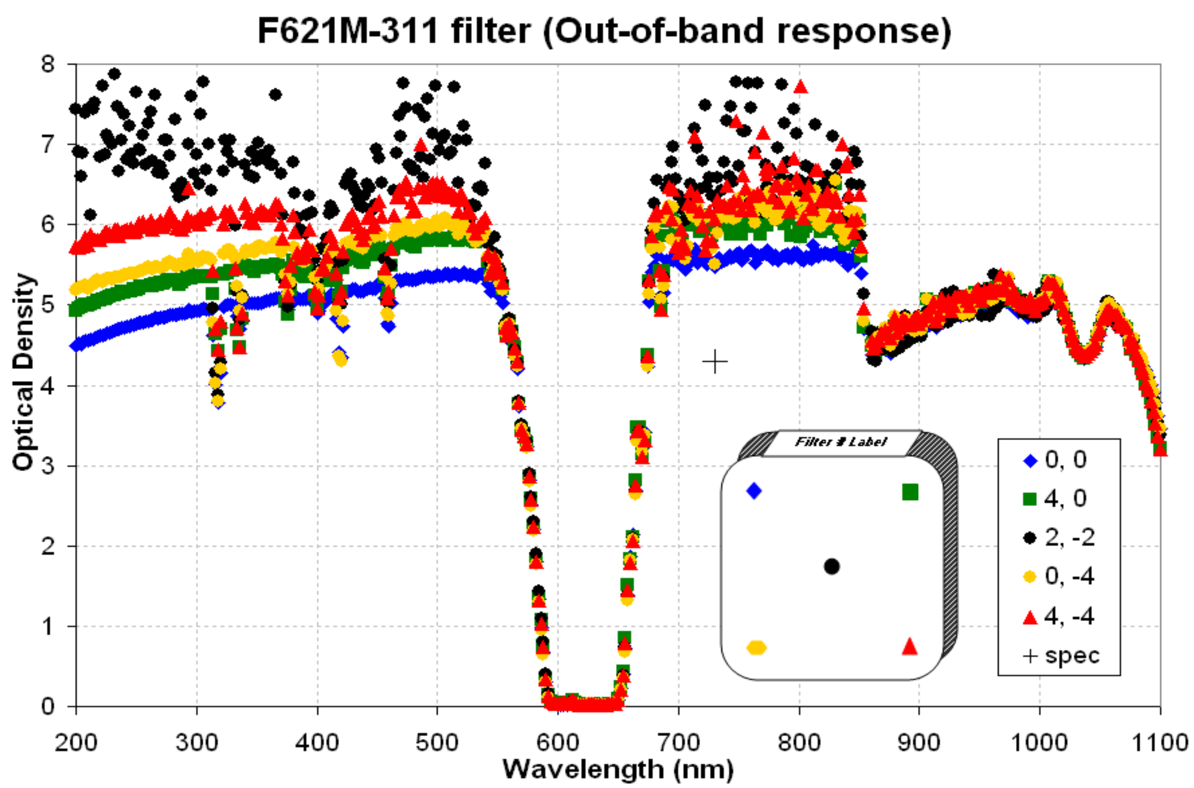

F600LP-003 (In-band response)
T
Wavelength (nm)
0, 0
1, 0
2, 0
3, 0
4, 0
0, -1
1, -1
2, -1
3, -1
4, -1
0, -2
1, -2
2, -2
3, -2
4, -2
0, -3
1, -3
2, -3
3, -3
4, -3
0, -4
1, -4
2, -4
3, -4
4, -4
spec
(λ.01 and λ.90 defined by RG610)
Filter # Label

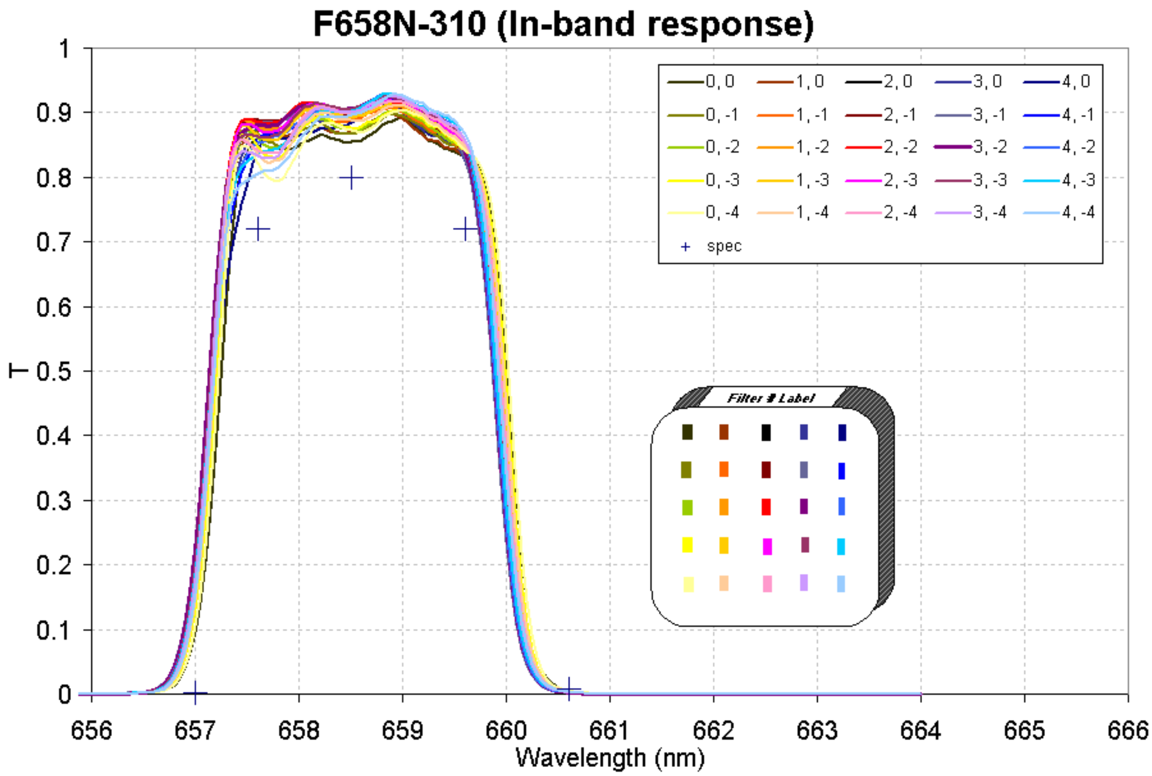

F600LP-003 (Out-of-band response)
Optical Density
Wavelength (nm)
Filter # Label
0, 0
4, 0
2, -2
0, -4
4, -4


F606W-310 (In-band response)
T
Wavelength (nm)
0, 0
1, 0
2, 0
3, 0
4, 0
0, -1
1, -1
2, -1
3, -1
4, -1
0, -2
1, -2
2, -2
3, -2
4, -2
0, -3
1, -3
2, -3
3, -3
4, -3
0, -4
1, -4
2, -4
3, -4
4, -4
spec
Filter # Label

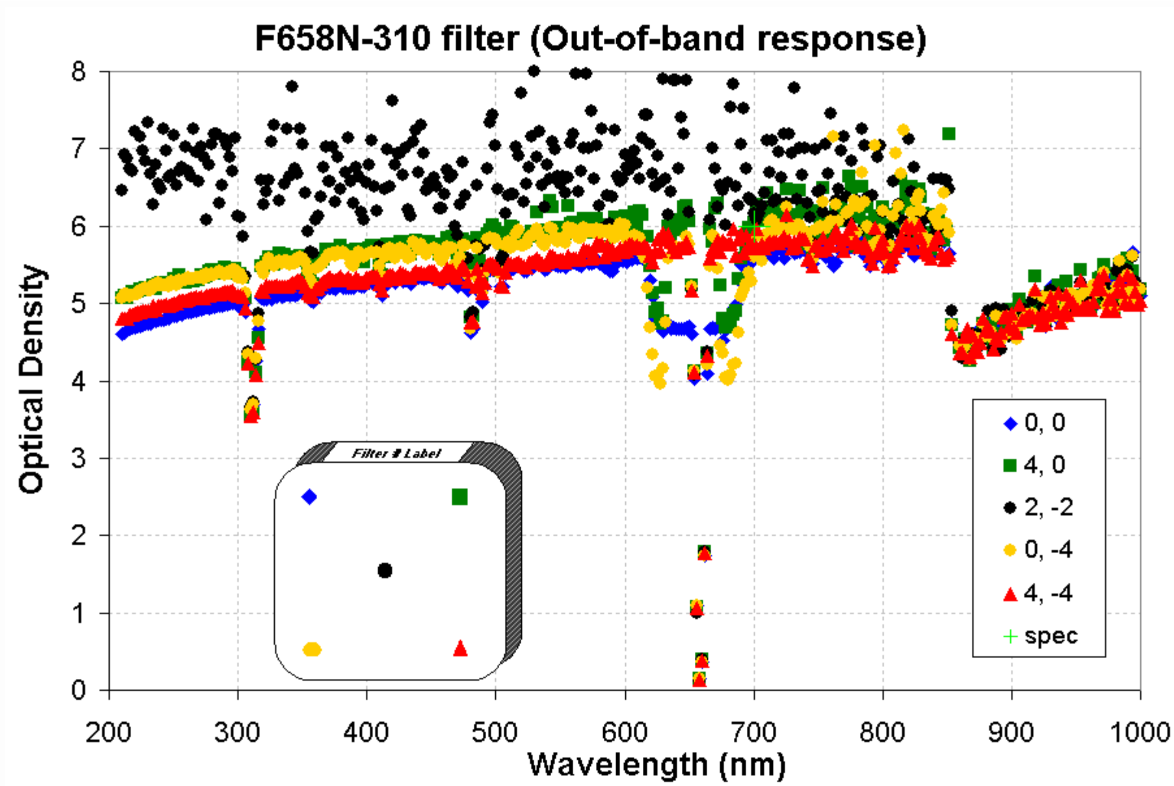

F606W-310 filter (Out-of-band response)
Optical Density
Wavelength (nm)
Filter # Label
0, 0
4, 0
2, -2
0, -4
4, -4
spec


F621M-311 (In-band response)
T
Wavelength (nm)
0, 0
1, 0
2, 0
3, 0
4, 0
0, -1
1, -1
2, -1
3, -1
4, -1
0, -2
1, -2
2, -2
3, -2
4, -2
0, -3
1, -3
2, -3
3, -3
4, -3
0, -4
1, -4
2, -4
3, -4
4, -4
spec
Filter # Label


F621M-311 filter (Out-of-band response)
Optical Density
Wavelength (nm)
0, 0
4, 0
2, -2
0, -4
4, -4
spec
Filter # Label



F658N-310 (In-band response)
T
Wavelength (nm)
0, 0
1, 0
2, 0
3, 0
4, 0
0, -1
1, -1
2, -1
3, -1
4, -1
0, -2
1, -2
2, -2
3, -2
4, -2
0, -3
1, -3
2, -3
3, -3
4, -3
0, -4
1, -4
2, -4
3, -4
4, -4
spec
Filter # Label



F658N-310 filter (Out-of-band response)
Optical Density
Wavelength (nm)
0, 0
4, 0
2, -2
0, -4
4, -4
spec
Filter # Label