Instrument Science Report WFC3

WFC3 IR Filters: Measured Throughput and Comparison to Specifications

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Abstract

This ISR presents the WFC3 IR filter throughput at the center of each filter as measured by the Optics Branch at Goddard Space Flight Center (R. Boucarut, M. Quijada and S. Struss). The measured data are compared to the WFC3 CEI specifications and to the design requirements outlined in the GSFC IR Filter specification document (GSFC 2001). Instrument throughput as a function of selected filter, out of band blocking conformance, as well as spatial trends will be documented in future ISRs.

Note: The intention of this study is to document the comparison between spec and as- built properties for future reference. Ultimately, the science goals determine the applicability of a specific filter. The WFC3 Science Oversight Committee has reviewed all the measured data, selected the flight candidates, and approved the filter deliveries.

1. Introduction

We present the Wide Field Camera 3 (WFC3) IR filter throughput measurements and compare the as-built qualities to the design specifications. Although we focus on the throughput and bandpass at the central regions of the filter in this ISR, future ISRs will document spatial trends as well as entire *instrument* throughput. The filter measurement program (Boucarut, Quijada, Lupie, Struss, and Miner 2002) was lead by the Optics Branch at Goddard Space Flight Center (R. Boucarut, M. Quijada and others). Assessment of conformance was carried out by Boucarut and Lupie. The intention of this ISR is to document the comparison between spec and as-built properties for future reference. Ultimately, the science goals determine the applicability of a specific filter. The WFC3 Science Oversight Committee has reviewed all the measured data, selected the flight candidates, and approved the filter deliveries from the vendors.

The **structure of this ISR** is as follows: Section 2 presents the throughput data and derived parameters in the form of annotated plots and tables. Definitions of all relevant filter characterization parameters are provided. Section 3 compares the throughput measurements to the specifications. Section 4 describes the requirements and GSFC measurements of wavefront, wedge, and focus shift. The document text closes with acknowledgements and references. Tables and figure panels may be found at the end of the text section.

The Wide Field Camera 3 program has spanned 3 years starting with the scientific selection of wavelength ranges of interest followed by the filter definition and requirements phase, the vendor interface phase, receipt and measurement of the filter properties and the final selection of the flight candidates. The scientific selection process and interim results are documented in several ISRs (WFC3 ISRs 2000-07,08,09 and ISR 2002-10). The team responsible for the entire filter development program comprises the following:

- WFC3 Science Oversight Committee → recommended the selection of filters and chose the final flight candidates.
- GSFC (Boucarut) and STScI (Lupie) → designed the IR filters specifications.
- Barr Associates, Inc → manufactured the filters.
- GSFC team (Boucarut et al.,) → assessed filter quality and measured filter characteristics.
- Ball Aerospace → provided optical prescriptions and mounted the filters in the housings.
- STScI/GSFC/Ball Aerospace → provided scientific studies and technical support.

2. Filter Throughput Data

The WFC3 IR channel filter wheel contains 17 slots for spectral defining elements. One blank (opaque) slot also on the filter wheel is used to block external light during background calibrations, since the IR channel has no shutter mechanism. Two of the elements are grisms and the remaining 15 are composed of broad, medium, and narrow band filters. The IR grisms, G141 and G102, will be documented in a future ISR.

The substrate materials for most of the filters is *IR80*, an IR grade (non-water absorbing) glass. Acceptance testing was performed at two temperatures, 20C and –40C (+/-5C), the latter being the in-orbit operating temperature of the filters. The requirements state that no deterioration or change of spectral characteristics may be present following temperature cycling from 25 to –40C.
Testing procedures, scientific method, and error budget analyses are well established, well documented and consistent with the needs of the WFC3 program. The acceptance and measurement techniques may be found in (Boucarut et al., 2001).

2.1 Panel Annotations

Panels 1 through 7 are plots of the measured throughput at the center of each IR filter as a function of wavelength. Design requirements (referred to as 'spec') and measured (as-built) and derived parameters are also indicated in the panels. Data for the wide and medium band filters were measured by GSFC in units of 0.002 and 0.001 microns respectively. Narrow band filter throughput was sampled at 0.00025 micron steps over the "in-band" regime and larger step sizes farther out in the wings of the throughput profile. The data were measured at 5 positions on each filter (center, right, left, top, and bottom) and at two temperatures, 296K and 243K. The data presented here are obtained at 296K because the trend with temperature is not appreciable. Spatial trends across the filter, though larger than spec, are within the science requirements and will be characterized in a future ISR.

2.1.1 Spectral Requirements

For detailed explanations of the requirements definitions and tolerances, we refer the reader to ISR WFC3-2000-09 (Lupie and Boucarut 2000). Summaries definitions are provided here for convenience.

Spectral Performance
The spectral performance requirements are given in terms of *critical* wavelengths, i.e., wavelengths at which the transmittance on either side of the passband equals a certain percentage of the peak, and remains less than that value for all shortward and longward wavelengths. The critical wavelengths include λ_{+50}, λ_{-50}, λ_{-80}, λ_{+80}, λ_{-90}, λ_{+90} and λ_{-01}, λ_{+01}. In each panel, a dotted rectangle outlines the specs for the FWHM defined at the wavelengths where the transmittance is 50% or 90% for wide/medium and

narrow bands, respectively. The height of this rectangle happens to coincide with the measured peak of the filter. The required central wavelength is labeled by the dotted vertical line halfway between the 50% critical wavelengths. One, two, or three horizontal dotted lines intersecting the dotted box identify the wavelengths at which the transmittance is 50% (all filters), 80% (wide and medium only), or 90% (most filters). Exceptions are F093W and F110W where the 50% points are specified in the plots. The blocking and bandpass shapes of these filters, manufacturing materials and techniques are very similar to F125W process. The narrow band specifications emphasize the 50 and 90% critical wavelengths. The required peak throughput, defined as the average absolute transmittance between λ_{-90} and λ_{+90}, is flagged by an arrow in the panels.

Bandpass

The width of the bandpass, drawn as a dotted rectangle (FWHM), is defined as [λ_{-50} - λ_{+50}]. For narrow bands, the [λ_{-90} - λ_{+90}] width is a more descriptive and stringent requirement for a rectangular filter. The rectangle is centered on the central wavelength.

Central Wavelength

The central wavelength stated in the requirements is the "center of mass" of the filter and is defined as the midpoint between either the 50% wavelengths or the 90% wavelengths depending on the filter category, i.e., broad/medium, or narrow.

Filter Shape

Although not shown on the panels, the required side slopes of the filters were provided to the vendors. The shape of the passband is a function of the number of "cavities" (or layers) in the design of the filter coating. The more cavities, the more square the filter, an advantageous characteristic for science programs. However, increasing the number of cavities also amplifies the peaks and valleys of the transmittance across the wavelength regime. Slopes of wide and medium band filters are calculated using ±5% and ±80% wavelengths, i.e., blue side slope = [λ_{-80} - λ_{-05}]/ λ_{-05}. Narrow band slopes were calculated using the ±1% and ±90% wavelengths . The maximum slope requirements are 1.5%, 1%, and 0.5% for wide, medium, and narrow band filters respectively. An alternative spec for the narrow band filters, specifically those that have accompanying continuum filters, the size of the overlap region was specified, i.e., the mutually-shared overlap of line and continuum filters (throughput vs wavelength) must be less than 10% of the area of the line filter.

Out of Band Blocking Requirements

The dynamic range of an instrument can be limited by a poorly designed out-of-band blocking requirement. Vendors require specification of the wavelength where the transmittance and ripples must not exceed the limiting value (e.g., 0.01% or 0.005%). The out-of-band blocking descriptors are not included in this report.

2.1.2 Tolerances

The IR Filter Specification document calls out the following tolerance criteria for in-band critical wavelengths:

Critical Wavelengths	Wavelength Tolerance	Minimum Wavelength Tolerance	Application
W-50, W+50	+/-20 A	+/-100 A	Wide/Medium Bands
W-90, W+90	+/-5 A	+/-20 A	Narrow Bands
W-01, W+01	+/-5 A	+/-20 A	Narrow Bands

2.1.2 As-Built Descriptions

Spectral Performance Parameters

Knowledge of the technique used to manufacture a filter is always infused in the statement of the specifications to the vendors. Modeling of filter coatings and substrate thickness are used to realistically set the performance requirements. This is why the requirements specifications may refer to different parameters depending on the type of filter being manufactured. As an example, for some of the wide band filters, one wavelength edge may be defined by the natural blocking of the color glass substrate used for that filter while the other edge may be sculpted by the type and thickness of the coating on the substrate. For most narrow bands, it is important that the peak of the filter be as flat and 'square' as possible. Therefore, specifying the 90% wavelengths is more descriptive to the vendor than providing the 50% FWHM points used to describe wider filters.

The measured wavelengths at which the transmittances are 0.01 absolute, 50%, 80%, and 90% of peak are denoted on the panels by a large asterisk and were calculated used a simple linear interpolation between to the two closest points to the specified transmittance.

Bandpasss

Two filter widths are denoted by horizontal dash-dot-dash lines with end brackets: 1) the full width half maximum of an equivalent Gaussian and 2) the rectangular width of the bandpass. These are labeled in the figures. The rectangular width is more suited for comparison with the FWHM specified in the requirements document.

Central Wavelength

Three descriptive "central wavelengths" are labeled using vertical dash-dot-dash line: *pivot, average, and mean*. Each of these three centralized wavelengths provide unique information about the filter's symmetry in wavelength space or frequency (energy) space. The *mean wavelength,* (originally described in Schneider, Gunn and Hoessel Ap.J 264,337 and then used to describe WFPC1 and WFCP2 filters), is used by astronomers to indicate the "center of mass" in terms of frequency, i.e., it represents the wavelength halfway between the "frequency" mean of the filter and the wavelength mean (WFPC2 Instrument Handbook – Appendix B, System Throughput Section). The *average wavelength* is the center of mass with respect to the area in the wavelength domain and is most closely related to the geometric mean wavelength specified in the GSFC requirements document. The *pivot wavelength* is the center of mass weighted by the inverse of the wavelength.

2.2 Table Descriptions

2.2.1 Requirements Specifications

Table 1 summarizes the performance requirements as stated in Version B, GSFC Filter Specifications Document (GSFC HST P442-3402) and modified by the change request documentation. The central wavelength and FWHM as specified in the "WFC3 Contract End Item Specifications" (WFC3 STE-66 baselined May 31, 2002) are consistent with the GSFC filter specs in all but two cases, F160W and F105W where the central wavelengths were adjusted for science reasons after the last update of the STE-66. These differences are highlighted in blue shading. The column definitions are as follows:

Column 1: F number – filter number designation used by the vendor.
Column 2: Science description.
Column 3: Filter name.
Column 4: Central Wavelength (microns):
$[\lambda_{-50} - \lambda_{+50}]/2$ for wide/medium bands or
$[\lambda_{-90} - \lambda_{+90}]/2$ for narrow bands.
Column 5: Central Wavelength (Shifted):
$[\lambda_{+50} - \lambda_{-50}]/2$ for wide/medium bands or
$([\lambda_{-90} - \lambda_{+90}]/2 + \delta\lambda)$ for narrow bands where $\delta\lambda$ is a redward shift of 500 km/sec.
Wide, medium and continuum narrow band central wavelengths are not redshifted.
Column 6: FWHM (microns): $[\lambda_{+50} - \lambda_{-50}]$ or $[\lambda_{+90} - \lambda_{-90}]$ for wide/medium and narrow bands respectively.
Column 7: Minimum average transmittance between [λ_{-90} and λ_{+90}].
Column 8: Fractional width (microns) defined as the FWHM divided by the central wavelength
Columns 9 through 16: the wavelengths at which the transmittance is the specified percentage of the peak and remains less than that value for all shorter and longer wavelengths (λ_{-01}, λ_{-50}, λ_{-80}, λ_{-90}, λ_{+90}, λ_{+80}, λ_{+50}, λ_{+01}). Blank cells indicate that the parameter was not describe the filter

Table 2 contains the out-of-band blocking requirements for the filter. The column definitions are:
Column 1: Filter Name
Column 2: Out-of-band blocking on the blue side: below a certain wavelength the transmittance shall not exceed the specified value.
Column 3: Wavelength pertaining to the out-of-band blocking requirement.
Column 4: Out-of-band blocking on the red side: below a certain wavelength the transmittance shall not exceed the specified value.
Column 5: Wavelength pertaining to the out-of-band blocking requirement.

2.2.2 Measurements

Table 3 contains descriptive properties of filters as calculated using integrals across the filter bandpasses. Wavelengths are given in Angstroms. The columns and parameter definitions are:
Column 1: Filter name.
Column 2: File name containing the filter name and the sample number – selected as flight filters.
Column 3: Pivot Wavelength – center of mass of the filter weighted by the inverse wavelength according to the following: $\sqrt{[(\int T(\lambda)\lambda d\lambda)/\int (T(\lambda)d\lambda/\lambda)]}$ where T is the transmittance.
Column 4: Bandwidth: RMS bandwidth.
Column 5: Equivalent Gaussian FWHM (note - most filters are not Gaussian in shape).
Column 6: Peak λ - wavelength of the peak transmittance.
Column 7: Peak Transmittance.

Column 8: Average Wavelength – straightforward "center of mass" of the filter according to the following: $\int T(\lambda)\lambda d\lambda / \int T(\lambda)d\lambda$.
Column 9: Rectangular Width – area divided by the peak: $\int [\ T(\lambda)d\lambda / \max(T(\lambda))]$
Column 10: Mean (or *bar)* Wavelength – wavelength of the center of mass in frequency space according to the following: $\exp[\ (\int T(\lambda)\ln(\lambda)d\lambda/\lambda)\ /\ (\int T(\lambda)d\lambda/\lambda)\ ]$.

Table 4 is a summary of the critical wavelengths, the measured FWHM and central wavelengths, and slopes of the filter bandpass:
Column 1: Filter name.
Column 2 through 9: the wavelengths where the measured transmittance is the specified percentage of the peak (λ_{-01}, λ_{-50}, λ_{-80}, λ_{-90}, λ_{+90}, λ_{+80}, λ_{+50}, λ_{+01}). Note that the 1% transmittance is an absolute transmittance.
Column 10: Measured Central Wavelength using $[\lambda_{+50} - \lambda_{-50}]/2$ or $[\lambda_{+90} - \lambda_{-90}]/2$ for wide/medium and narrow bands respectively.
Column 11: Measured FWHM (microns) defined as $[\lambda_{+50} - \lambda_{-50}]$ or $[\lambda_{+90} - \lambda_{-90}]$ for wide/medium and narrow band filters respectively.
Column 12: Measured Transmittance peak.
Column 13: Percent Blue-side Slope defined as $[\lambda_{-90} - \lambda_{-50}]/\lambda_{-50}$. Although we provide a single definition for the Blue slope here, the vendors were actually given several unique (stringent) instructions for many of the filters. For the purposes of this documentation, we provide the "pseudo-slope" using the 50% points instead of the 15 or 5%, points for illustration.
Column 14: Percent Red-side Slope defined as $[\lambda_{+90} - \lambda_{+50}]/\lambda_{+50}$. See explanation for Col. 13.

2.2.3 Comparison: Spec to As-Built

The specs, in several cases, were designed to *push* the limit of manufacturing capability, i.e., manufacturers were to interpret the specs as guidelines for ultimate performance goals.

Table 5 lists differences between spec and as-built performance parameters:
Column 1: Filter Name.
Columns 2 though 7: Differences between the spec and as-built critical wavelengths. The critical wavelengths are those at which the measured transmittance is the specified percentage of the peak. Blank cells indicate that the corresponding specification was not used for that filter.
Column 8: Delta Central Wavelength: difference between the spec and as-built Central Wavelength using
$[\lambda_{+50} - \lambda_{-50}]/2$ or $[\lambda_{+90} - \lambda_{-90}]/2$ for wide/medium and narrow bands respectively.
Column 9: Difference between the measured and as-built FWHM (microns) defined as $[\lambda_{+50} - \lambda_{-50}]$ or $[\lambda_{+90} - \lambda_{-90}]$ for wide/medium and narrow filters, respectively.
Column 10: Comparison of the spec and as-built peak transmittances.
Column 11: Difference between the measured "average wavelength" and the spec central wavelength, where the average wavelength is the straightforward "center of mass" of the filter according to the following: $\int T(\lambda)\lambda d\lambda / \int T(\lambda)d\lambda$. The average wavelength is given in Table 3.

3. As-Built Throughput Conformance - Discussion

The Contract End Item Specifications for the IR Filters are given in sections 4.4.6 of STE-66, version May 31, 2002. The requirement states that the channel should include at least 15 with a goal of 20 selectable spectral defining elements (CEI-Table 4-7, and see Table 1 in this ISR columns 3 and 4). Tolerances on the central wavelength and width are specified in the GSFC design requirements. All parties share the understanding that the vendor was to perform "best effort" especially since many of the filters (and filter quality) are quite unique. Ultimately, the Science Oversight Committee has determined whether a filter fit the particular science need. *As a compromise for the purposes of an overall performance verification, a tolerance has been adopted to identify those filters whose performance spec satisfy the needs of the science community but do not conform completely to the performance specifications*.

Wide and Medium Bands

The tolerances on the critical wavelengths for the wide bands are ±100A with a goal of ±20A (best effort) and measurements were made in increments of 20A and 10A for the wide and medium filters respectively. Table 5 demonstrates that 50,80, and 90% critical wavelengths are well within the 100A tolerance. The 50% critical wavelengths of all but F105W is within a factor of 2 of the 20 A goal. The 1% absolute points measured by GSFC are not included in Table 5 but are in conformance with the scientific requirements.

Narrow Band

The critical wavelengths that best describe the narrow bands are the 1% and 90% points. The tolerances on the critical wavelengths are ±20A with a goal of ±5A (best effort) and measurements were made in increments of ~2.5A in the in-band regime of the filter. Table 5 demonstrates that 90% critical wavelengths are well within the 20A tolerance and the central wavelength and FWHM also meet the scientific specification. The 1% absolute points measured by GSFC are not included in Table 5 but are in conformance with the scientific requirements.

4. Types of Elements, Image Displacement and Transmitted Wavefront

The Contract End Item Specifications for the IR Filter elements given in sections 4.4.6 of STE-66, also include the image quality, parfocality condition, wedge, types of elements and their location in the optical train.

4.1 Section 4.4.6.1 and 4.4.6.2 CEI: Types and Numbers of IR Spectral Elements

The CEI requires *at least* 15 selectable spectral defining elements (with a goal of 20) in the WFC3 IR channel as listed in the **CEI Table 4-7** (see Table 1 in this ISR columns 3 and 4). There are indeed 17 selectable spectral defining elements. Two of these are grisms and the remaining 15 are composed of broad, medium, and narrow filters.

4.2 Section 4.4.6.4 CEI: Performance of Spectral Elements - Image Quality, Parfocality, Wedge

Additional performance requirements state that a mounted filter must not displace the image by more than 0.2 detector pixels or degrade image quality by more than 0.02 waves at 633 nm of transmitted wavefront before mounting in the filter wheel. This requirement guarantees positional and performance consistency between measurements obtained with different filters.

The GSFC Requirements detail the focus shift, wedge, and transmitted wave front. The focus shift of each filter must equal the focus shift of a 4.0 mm thick plano/plano IR fused silica substrate at wavelengths 6330 Angstroms (refractive index 1.450416). The focus shift equation insures the parfocality of the filters: $K = (n-1)t/n = 1.242171$ where n is the index of the substrate at 1 micron and t = 4mm. The allowable wedge is specified as 10 arcsec or less across 22 mm aperture. The results of the GSFC and vendor measurements of the focus shift, transmitted wavefront, were provided by Boucarut (private communication).

Table 6 contains the thickness and measured wavefront. Each individual substrate wedge was measured prior to the filter manufacturing process at two positions. From these numbers we can derive an upper limit on the wedge properties of the filter. Measurements of the *reflected* wavefront for all but two of the

filters were made on each side of the filter. For filters F110W and F125W, the *transmitted* wavefront was measured. The columns in Table 6 are defined as follows:
Column1: Filter Name.
Column 2: Filter Sample Number.
Columns 3 and 4: Filter thickness in (mm) at two positions on the filter.
Column 5: Filter Diameter (mm).
Columns 6 and 7: Reflected (or Transmitted for F110W and F125W) Wavefront RMS over the full clear aperture of 22mm.

5. Summary

We have described the as-built characteristics of the IR filters and compared some basic design requirements to measured parameters. The filter construction and properties conform the needs of the WFC3 Design Reference Mission and anticipated WFC3 science programs. This ISR focuses on the basic filter throughput and bandpass characteristics. Future ISRs will describe the spatial trends across the filters, the grisms, and the out of band blocking conformance.

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Table 1: WFC3 Infrared Filter Requirements

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
				shift 500 km/sec											
			AIR	AIR			AIR	AIR	AIR	AIR	AIR	AIR	AIR	AIR	AIR
#	Science Equivalent	Filter	lam0 microns	lamc microns central	FWHM microns	%Tran	del lam/ lam	W-01 microns	W-50 microns	W-80 microns	W-90 microns	W+90 microns	W+80 microns	W+50 microns	W+01 microns
1	**Broad H and Red Grism Ref ***	**F160W**	1.54500	1.54500	0.290000	98	0.18770	1.38329	1.40000	1.41023	1.41364	1.67636	1.67977	1.69000	1.70671
2	**Broad J**	**F125W**	1.25000	1.25000	0.300000	98	0.24000	1.08616	1.10000	1.10848	1.11130	1.38870	1.39152	1.40000	1.41384
3	**"Red" Low Resolution Grism**	**G141**	1.41000		0.600000		0.42553								
6	**Water/CH_4 continuum**	**F127M**	1.27000	1.27000	0.070000	98	0.05512	1.22642	1.23500	1.24025	1.24200	1.29800	1.29975	1.30500	1.31358
7	**Water/CH_4 line**	**F139M**	1.38500	1.38500	0.070000	98	0.05054	1.34067	1.35000	1.35571	1.35762	1.41238	1.41429	1.42000	1.42933
8	**"Blue" High Resolution Grating**	**G102**	1.02500		0.250000		0.24390								
17	**"Blue" Filter, Blue Grism Ref ***	**F098M**	0.98500	0.98500	0.170000	98	0.17259	0.89290	0.90000	0.90431	0.90574	1.06426	1.06569	1.07000	1.07703
10	**[FeII]**	**F164N**	1.64355	1.64629	0.016463	95	0.01002	1.63477	1.63806		1.63806	1.65452		1.65452	1.65781
11	**[FeII] continuum**	**F167N**	1.66770	1.66770	0.016677	95	0.01000	1.65603	1.65936		1.65936	1.67604		1.67604	1.67937
12	**H_20 and NH_3**	**F153M**	1.53000	1.53000	0.070000	95	0.04575	1.48471	1.49500	1.50130	1.50340	1.55660	1.55870	1.56500	1.57529
13	**Paschen Beta**	**F128N**	1.28181	1.28395	0.012839	95	0.01002	1.27496	1.27753		1.27753	1.29037		1.29037	1.29293
14	**Paschen Beta continuum**	**F130N**	1.30060	1.30060	0.013006	95	0.01000	1.29150	1.29410		1.29410	1.30710		1.30710	1.30970
15	**[FeII]**	**F126N**	1.25702	1.25912	0.012591	95	0.01002	1.25030	1.25282		1.25282	1.26541		1.26541	1.26793
16	**Paschen Beta (redshifted)**	**F132N**	1.32000	1.32000	0.013200	95	0.01000	1.31076	1.31340		1.31340	1.32660		1.32660	1.32924
18	**Wide FAT "z"**	**F105W**	1.05000	1.05000	0.300000	95	0.28571	0.89290	0.90000	0.90431	0.90574	1.19031	1.19273	1.20000	1.21187
20	**Wide Band passes 633nm**	**F093W**	0.83500	0.83500	0.470000	95			0.60000					1.07000	
19	**Wide J (equal H area)**	**F110W**	1.15000	1.15000	0.500000	95			0.90000			1.38870	1.39152	1.40000	1.41384

Table 2: Out-of-Band Blocking Requirements

1	2	3	4	5
Filter	Blue-side Block	Blue-Side Block Wave microns	Red-side Block	Red-Side Block Wave microns
F160W	1.00E-04	0.9820	5.00E-05	
F125W	1.00E-04	0.9177	5.00E-05	1.5823
F127M	5.00E-05	1.1744	5.00E-05	1.3656
F139M	5.00E-05	1.2966	5.00E-05	1.4734
F098M	5.00E-05	0.8500	5.00E-05	1.1868
F164N	1.00E-05	1.6135	1.00E-05	1.6791
F167N	1.00E-05	1.6345	1.00E-05	1.6995
F153M	5.00E-05	1.4409	5.00E-05	1.6190
F128N	1.00E-05	1.2593	1.00E-05	1.3086
F130N	1.00E-05	1.2752	1.00E-05	1.3260
F126N	1.00E-05	1.2337	1.00E-05	1.2845
F132N	1.00E-05	1.2945	1.00E-05	1.3455
F105W	1.00E-04	0.8500	5.00E-05	1.3100
F093W				
F110W				1.5823

Table 3: Calculated Descriptive Parameters

1	2	3	4	5	6	7	8	9	10
Filter	**Filter Sample Name**	**Pivot[1] Wave**	**RMS Bandwidth**	**Gauss FWHM**	**Wave Peak T**	**Peak Trans.**	**Average[2] Wave**	**Rect. Width**	**Mean[3] Wave**
		(A)	**(A)**	**(A)**	**(A)**		**(A)**	**(A)**	**(A)**
F093W	i_F093W_001_trns.tab	8273.66	1326.69	3124.13	8425.09	0.989	8384.41	4401.71	7840.07
F098M	i_F098M_004_trns.tab	9829.31	493.91	1163.06	9379.55	0.970	9841.78	1645.86	9779.58
F105W	i_F105W_001_trns.tab	10489.53	844.41	1988.43	9879.32	0.984	10523.84	2813.09	10352.89
F110W	i_F110W_002_trns.tab	11377.51	1427.48	3361.47	11819.16	0.994	11469.22	4780.07	11015.25
F125W	i_F125W_003_trns.tab	12449.36	855.94	2015.58	11680.25	0.977	12479.02	2902.19	12331.24
F126N	i_F126N_001_trns.tab	12582.59	44.69	105.23	12574.48	0.897	12582.67	148.02	12582.26
F127M	i_F127M_002_trns.tab	12736.38	207.23	488.00	12979.23	0.976	12738.07	682.74	12729.60
F128N	i_F128N_002_trns.tab	12832.98	47.51	111.89	12788.18	0.939	12833.07	154.30	12832.63
F130N	i_F130N_001_trns.tab	13006.22	68.17	160.52	13030.92	0.965	13006.39	154.19	13005.55
F132N	i_F132N_001_trns.tab	13190.44	54.11	127.41	13179.89	0.911	13190.59	158.01	13189.95
F139M	i_F139M_001_trns.tab	13838.04	193.61	455.92	14070.88	0.977	13839.40	638.98	13832.56
F153M	i_F153M_002_trns.tab	15333.07	206.05	485.21	15119.33	0.981	15334.48	686.07	15327.33
F160W	i_F160W_00s_trns.tab	15405.16	828.32	1950.55	14440.78	0.984	15427.52	2794.66	15315.88
F164N	i_F164N_001_trns.tab	16451.30	61.56	144.95	16432.60	0.931	16451.40	205.08	16450.75
F167N	i_F167N_002_trns.tab	16672.60	62.76	147.80	16701.79	0.933	16672.73	208.23	16672.15

[1]Pivot Wavelength: center wavelength weighted by 1/λ

[2]AVG Wave: "center of mass" of the filter.

[3]Wavelength half way between wavelength and frequency bandpass center averages.

Table 4: Measured Performance at Critical Wavelengths.

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Filter	**Meas W-01 (A)**	**Meas W-50 (A)**	**Meas W-80 (A)**	**Meas W-90 (A)**	**Meas W+90 (A)**	**Meas W+80 (A)**	**Meas W+50 (A)**	**Meas W+01 (A)**	**Meas[1] Cen Wave (A)**	**FWHM[2] (50% or 90%) (A)**	**Meas T peak (A)**	**%Slope[3] blue side**	**%Slope[3] red side**
F093W		6038.9					10684.7		8361.8	4645.8	0.99		
F098M	8711.9	8999.8	9026.9	9039.6	10643.4	10662.4	10694.6	11087.0	9847.2	1694.8	0.97	0.44	-0.48
F105W	8719.6	9059.6	9092.7	9116.8	11949.0	11961.4	11982.6	12380.1	10521.1	2923.0	0.98	0.63	-0.28
F110W		8975.0					13986.2		11480.6	5011.2	0.99		
F125W	10323.2	10997.9	11022.6	11036.7	13858.8	13933.4	13975.6	14478.2	12486.8	2977.7	0.98	0.35	-0.84
F126N	12372.5	12507.9		12521.7	12640.0		12657.6	12777.8	12582.8	118.3	0.90	0.11	-0.14
F127M	11909.1	12391.5	12418.0	12435.0	13036.3	13050.0	13079.4	13590.9	12735.5	687.9	0.98	0.35	-0.33
F128N	12602.6	12754.3		12765.7	12901.1		12912.8	13096.9	12833.6	135.4	0.94	0.09	-0.09
F130N	12011.0	12927.6		12939.4	13072.2		13084.0	13989.2	13005.8	132.8	0.96	0.09	-0.09
F132N	12210.9	13110.3		13124.0	13254.7		13271.3	14188.8	13190.8	130.7	0.91	0.10	-0.13
F139M	13009.1	13513.3	13537.7	13557.0	14119.7	14132.1	14159.1	14690.3	13836.2	645.8	0.98	0.32	-0.28
F153M	14508.9	14988.5	15016.4	15036.5	15631.4	15646.2	15676.3	16190.4	15332.4	687.8	0.98	0.32	-0.29
F160W	13520.3	13992.3	14027.0	14059.4	16779.3	16839.6	16871.1	17359.5	15431.7	2878.8	0.98	0.48	-0.54
F164N	16202.7	16348.8		16364.6	16539.4		16555.5	16697.3	16452.2	174.8	0.93	0.10	-0.10
F167N	16452.4	16566.6		16585.6	16757.2		16776.9	16897.5	16671.8	171.6	0.93	0.11	-0.12

[1]**Measured Central Wavelength calculated using 50% wavelengths.**

[2]**FWHM calculated used 50% or 90% wavelengths.**

[3]**Slope between 90% and 50% wavelengths.**

Table 5:Continuation: Performance Parameters: Spec and As-Built

1	2	3	4	5	6	7	8	9	10	11
Filter	Meas-Spec[1] W-50 (A)	Meas-Spec W-80 (A)	Meas-Spec[2] W-90 (A)	Meas-Spec[2] W+90 (A)	Meas-Spec W+80 (A)	Meas-Spec[1] W+50 (A)	Meas-Spec[3] Cen Wave (A)	Meas-Spec[4] FWHM (A) at 50%	Meas-Spec T peak	Meas-Spec[5] AVG Wave (A)
F093W	38.9					-15.3	11.8	-54.2	0.04	34.4
F098M	-0.2	-16.2	-17.8	0.8	5.5	-5.4	-2.8	-5.2	-0.01	-8.2
F105W	59.6	49.6	59.4	45.9	34.1	-17.4	21.1	-77.0	0.03	23.8
F110W	-25.0					-13.8	-19.4	11.2	0.04	-30.8
F125W	-2.1	-62.2	-76.3	-28.2	18.2	-24.4	-13.3	-22.3	0.00	-21.0
F126N	-20.3		-6.5	-14.1		3.5	-8.4	23.8	-0.05	-8.5
F127M	41.5	15.5	15.0	56.3	52.5	29.4	35.5	-12.1	0.00	38.1
F128N	-21.0		-9.6	-2.6		9.1	-5.9	30.1	-0.01	-6.4
F130N	-13.4		-1.6	1.2		13.0	-0.2	26.3	0.01	0.4
F132N	-23.7		-10.0	-11.3		5.3	-9.2	29.0	-0.04	-9.4
F139M	13.3	-19.4	-19.2	-4.1	-10.8	-40.9	-13.8	-54.2	0.00	-10.6
F153M	38.5	3.4	2.5	65.4	59.2	26.3	32.4	-12.2	0.03	34.5
F160W	-7.7	-75.3	-77.0	15.7	41.9	-28.9	-18.3	-21.2	0.00	-22.5
F164N	-31.8		-16.0	-5.8		10.3	-10.8	42.1	-0.02	-11.5
F167N	-27.0		-8.0	-3.2		16.5	-5.3	43.5	-0.02	-4.3

[1]For Wide and Medium Band Filters use 50% wavelengths: Goal = 20A, Minimum = 100A.

[2]For Narrow Bands use 90% wavelengths: Goal = 5A, Minimum = 20A.

[3]Measured Central Wavelength calculated using 50% wavelengths.

[4]FWHM calculated used 50% wavelengths.

[5]AVG Wave: "center of mass" of the filter (see text).

Table 6: Measured Filter Thickness and Wavefront

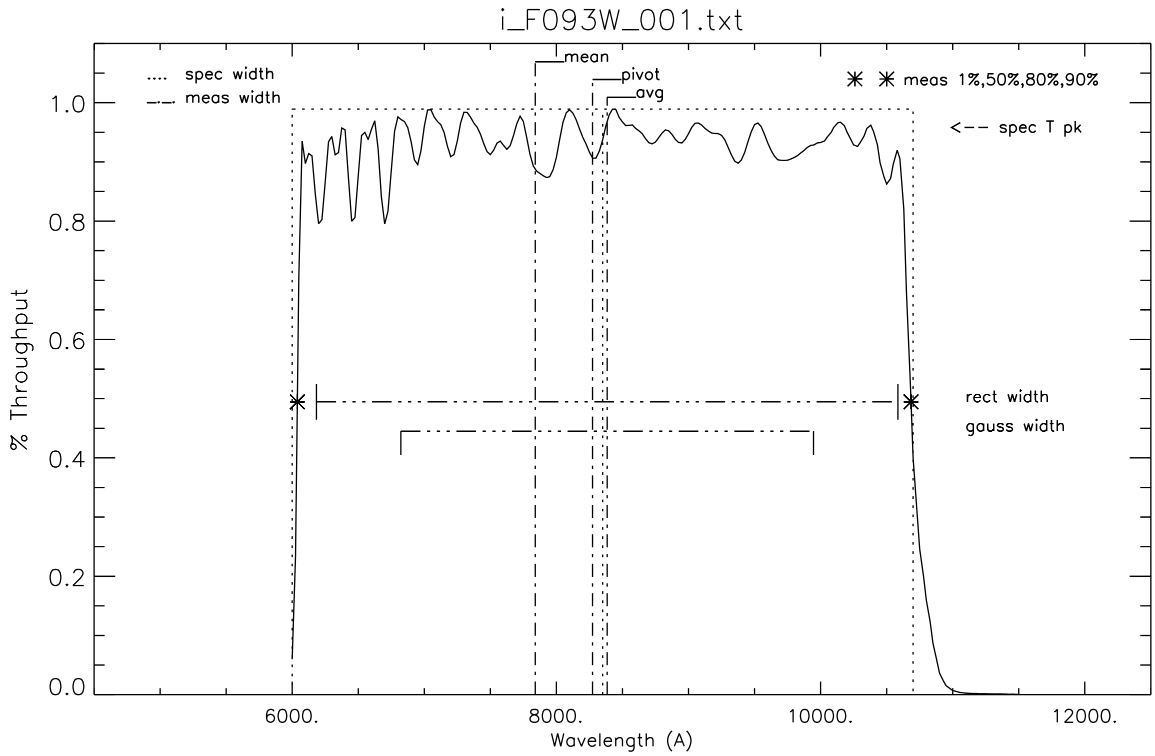
1	2	3	4	5	6	7
Filter name	**Serial Number**	**Thickness[1] position 1 (mm)**	**Thickness[1] position 2 (mm)**	**Diameter[3] (mm)**	**Side a[3] wavefront rms**	**Side b[3] wavefront rms**
F093W	001	4.11	4.12	25.46	0.045	
F098M	004	3.65	3.65	25.31	1.207	1.162
F105W	001	3.64	3.64	25.22	0.844	0.755
F110W	002	4.13	4.13	25.43	0.173	
F125W	003	4.13	4.13	25.47	0.068	
F126N	001	3.66	3.66	25.33	1.082	1.032
F127M	002	3.63	3.63	25.32	1.845	0.582
F128N	002	3.67	3.67	25.22	1.277	0.439
F130N	001	3.67	3.66	25.33	0.227	0.177
F132N	001	3.65	3.66	25.41	0.196	0.629
F139M	001	3.64	3.64	24.35	0.778	0.578
F153M	002	3.64	3.64	25.35	0.621	0.927
F160W	001	3.66	3.66	25.32	1.002	1.058
F164N	001	3.65	3.65	25.35	0.521	0.666
F167N	002	3.67	3.67	25.41	0.790	1.210

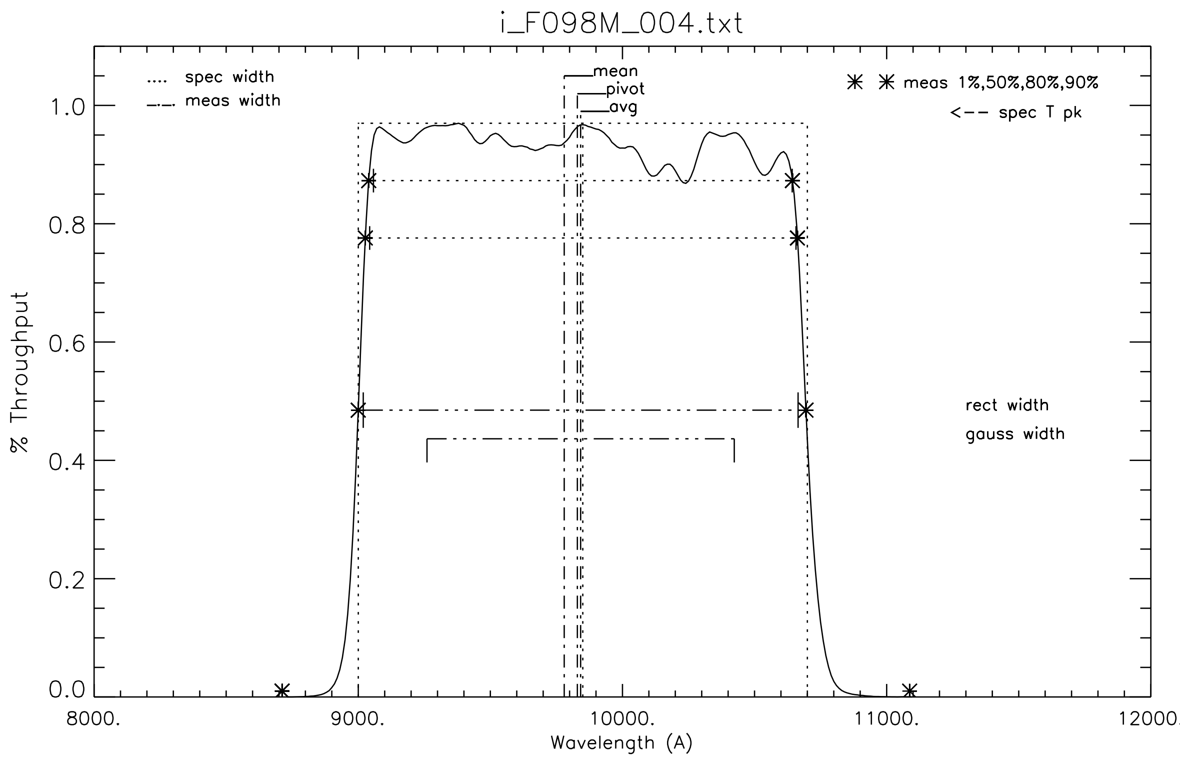
[1]Thickness measured at two spots on the filter. IR80 glass thickness = 3.66 mm

[2] Outer Filter Diamter specification = 25.4 mm

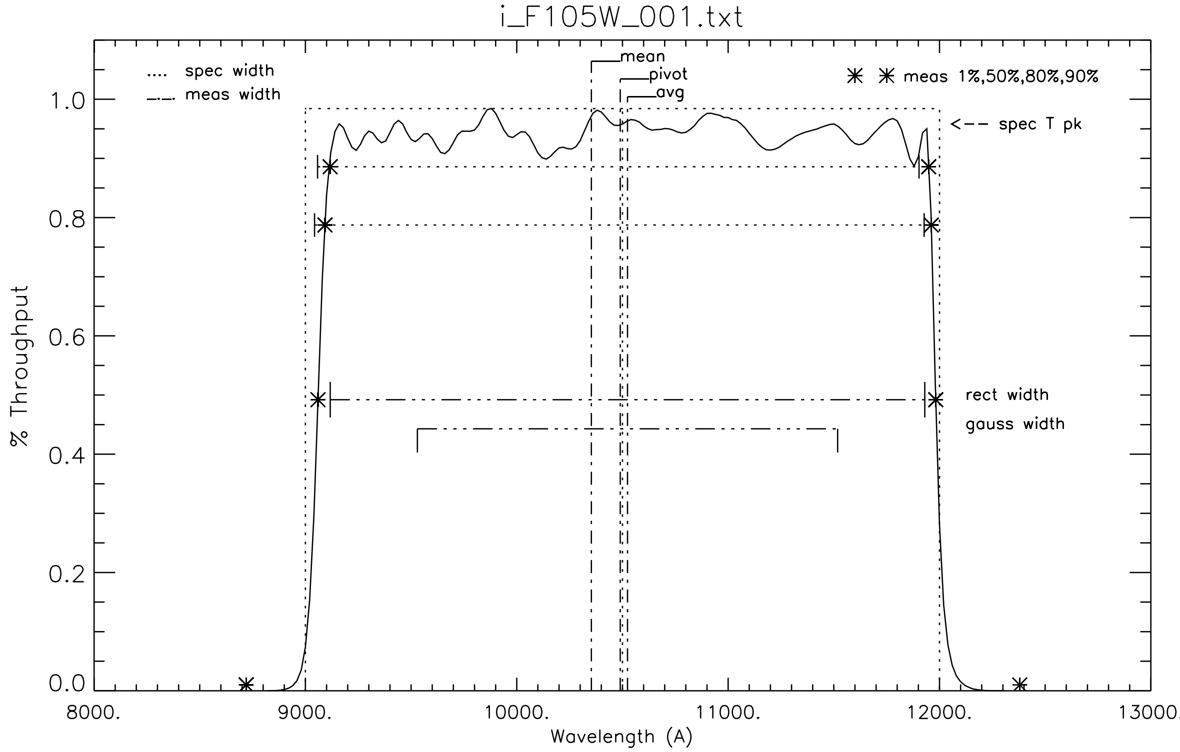
[3] Reflected Wavefront measurement.

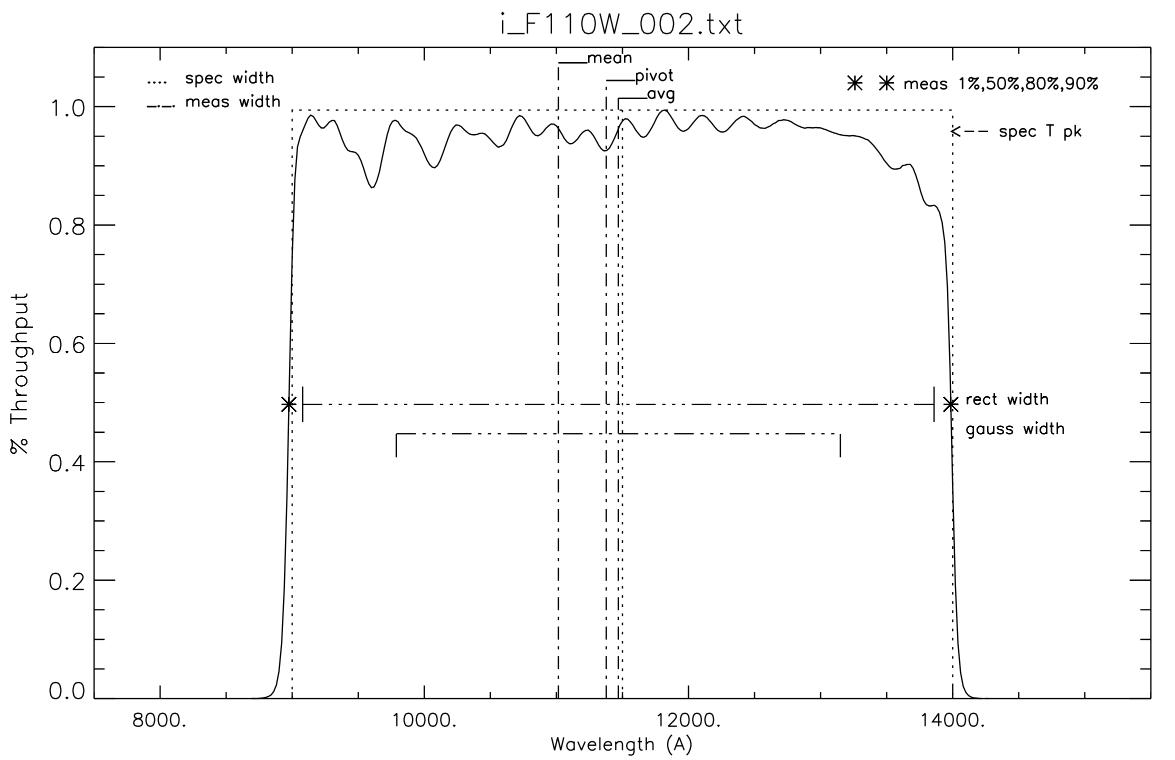
Panel 1: WFC3 IR Filters



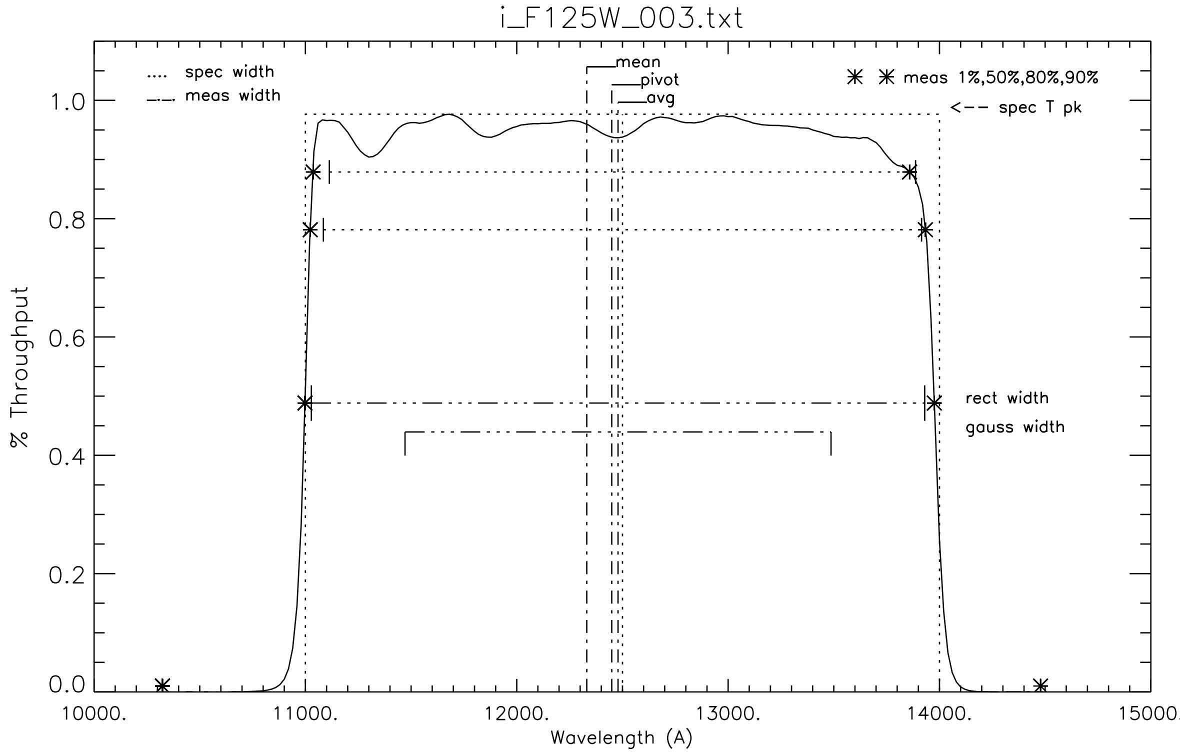


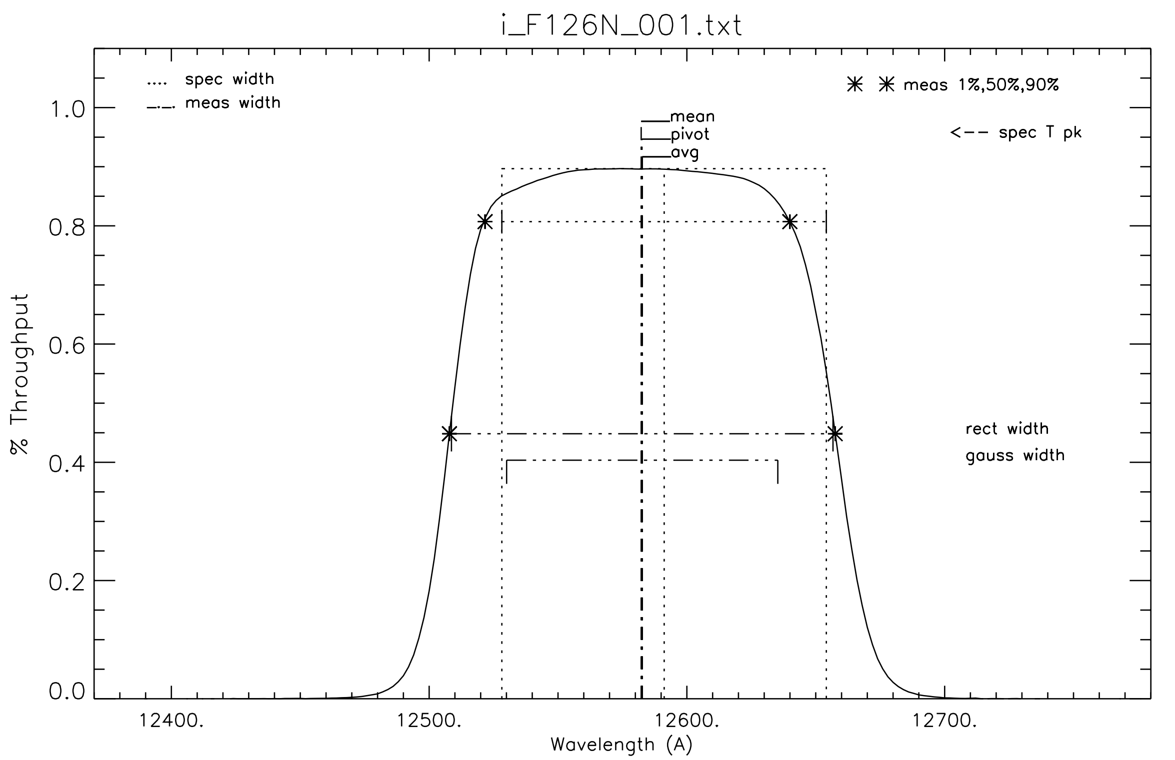
Panel 2: WFC3 IR Filters



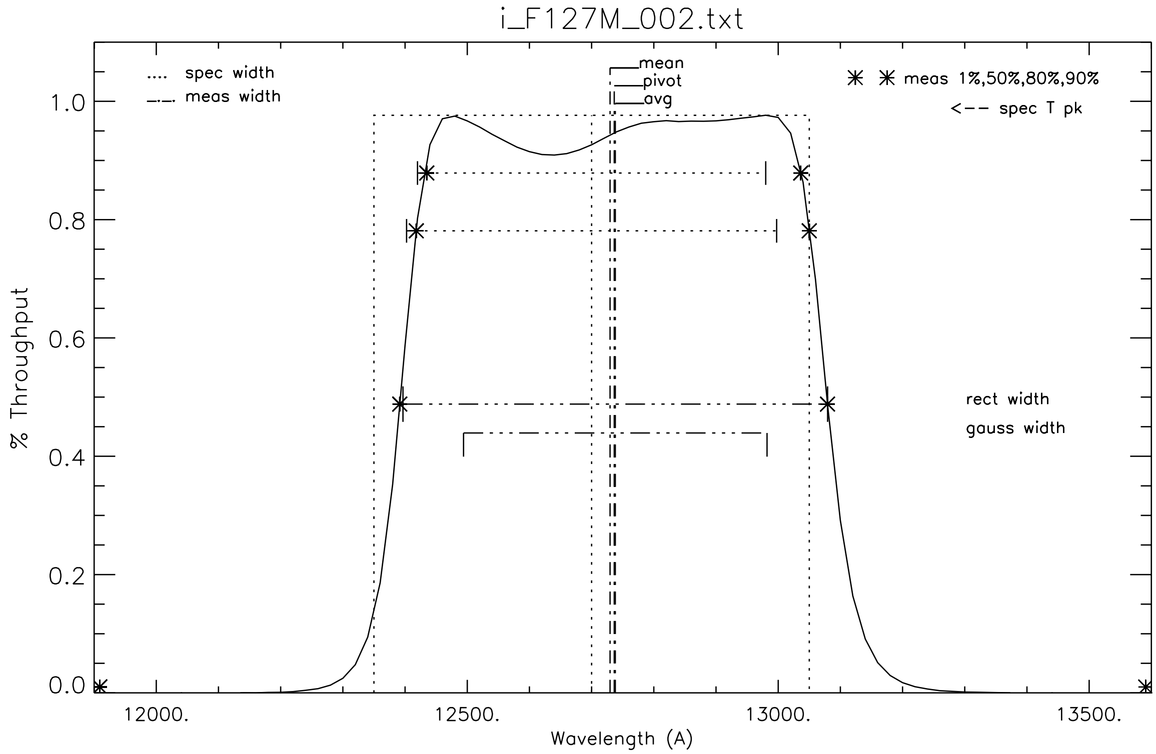


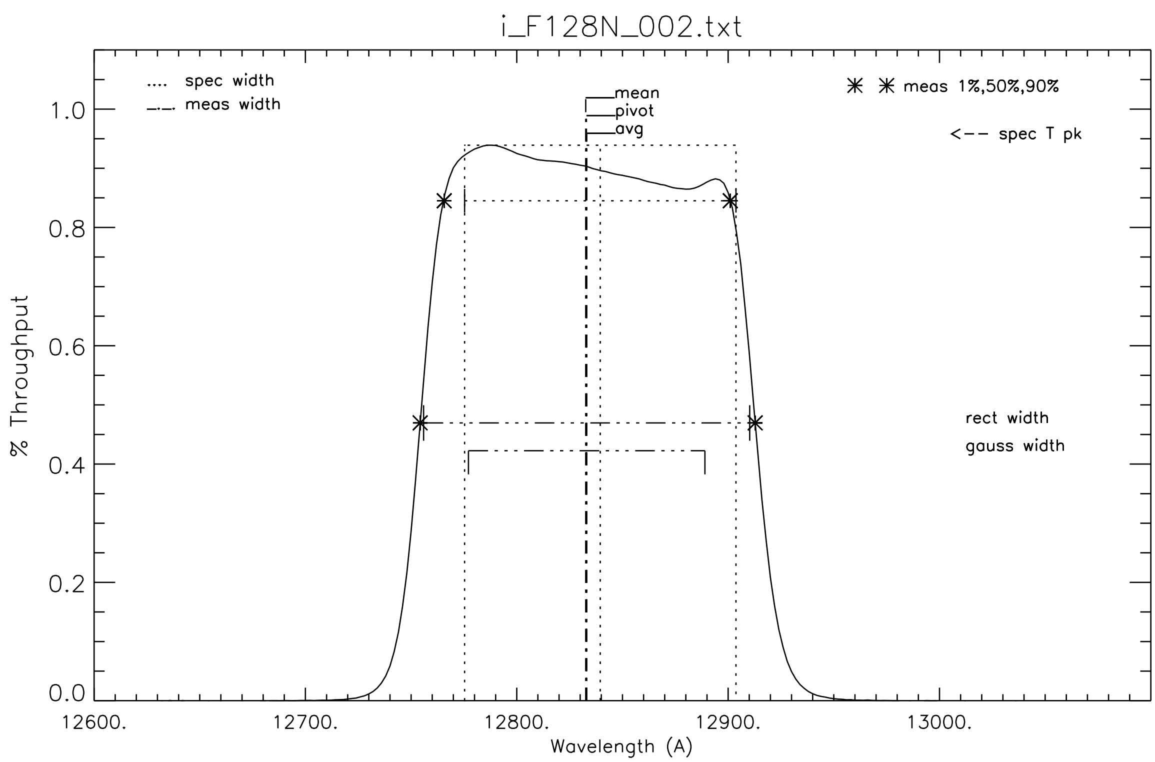
Panel 3: WFC3 IR Filters



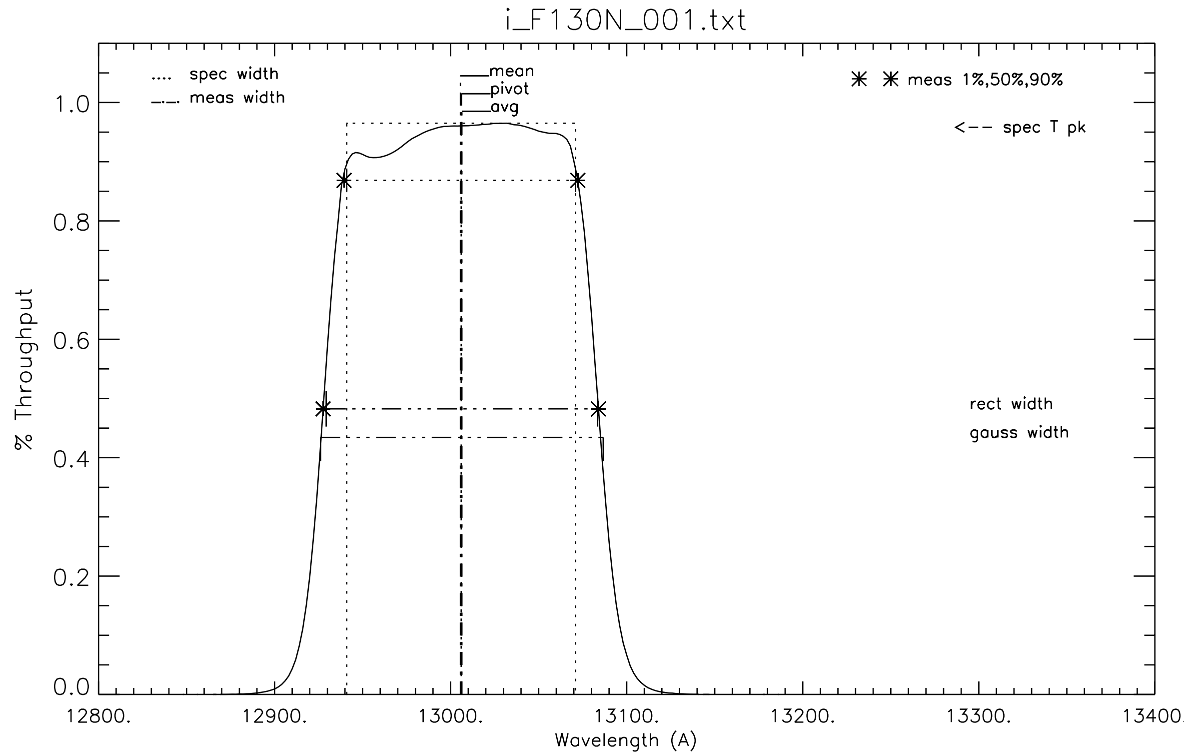


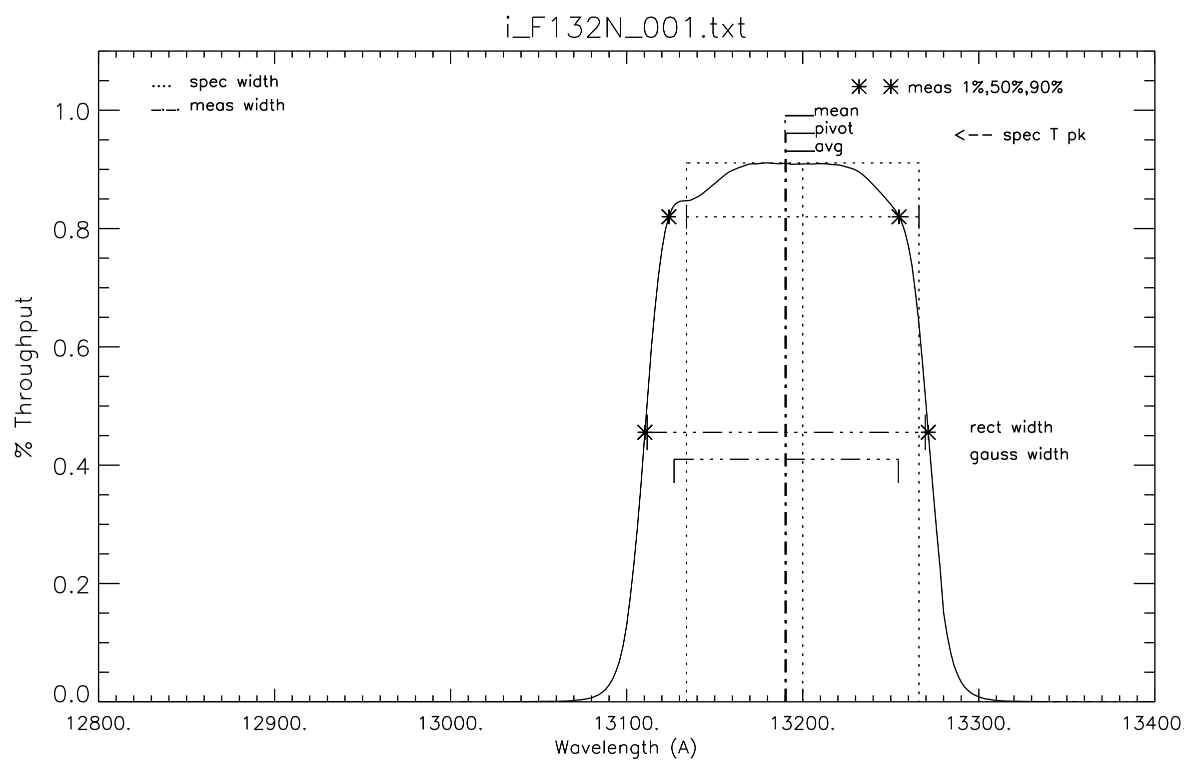
Panel 4: WFC3 IR Filters



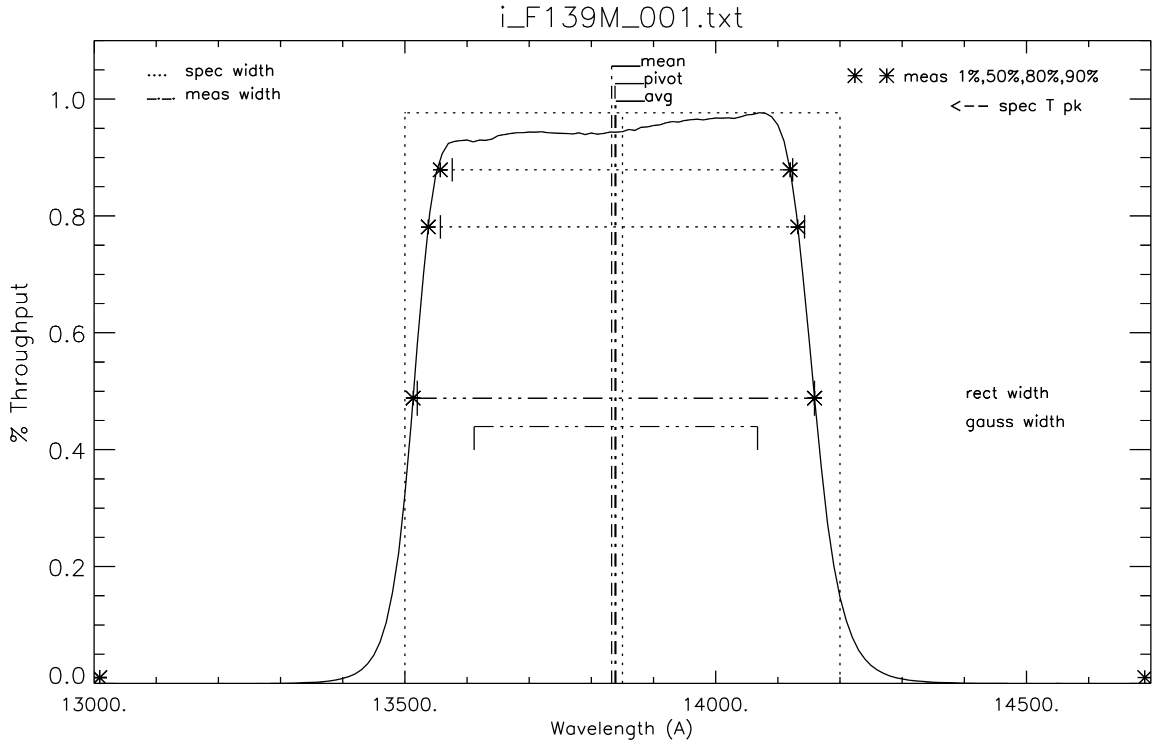


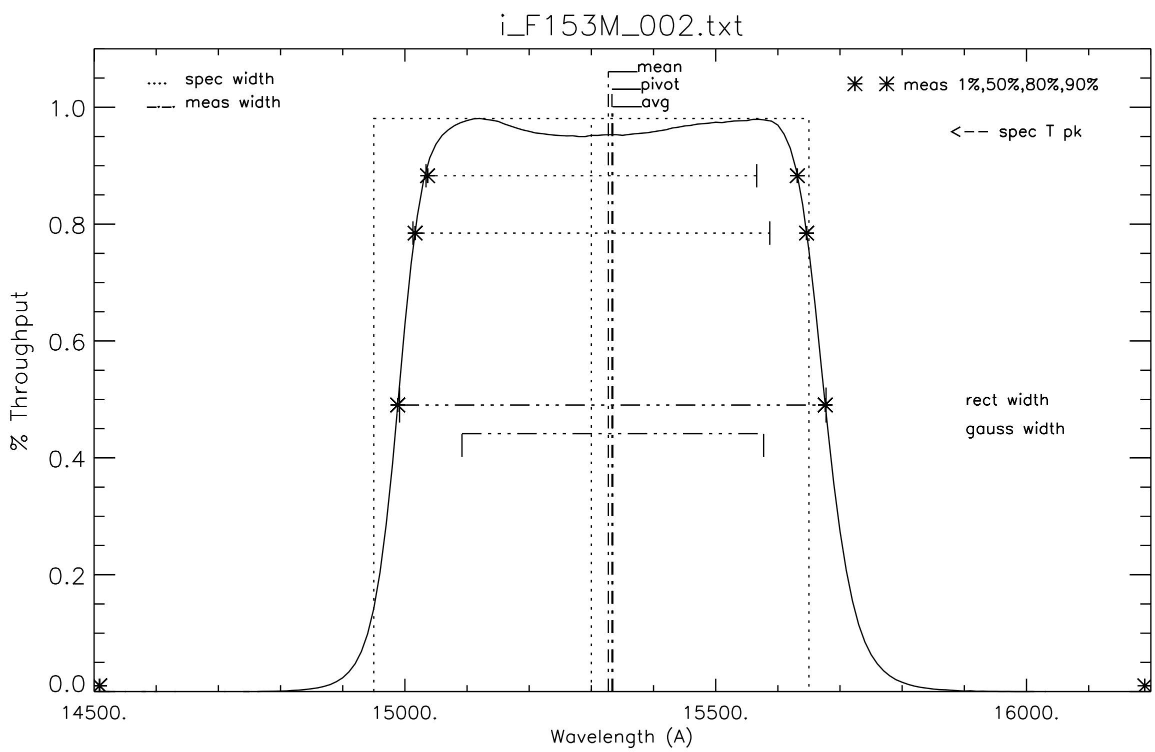
Panel 5: WFC3 IR Filters



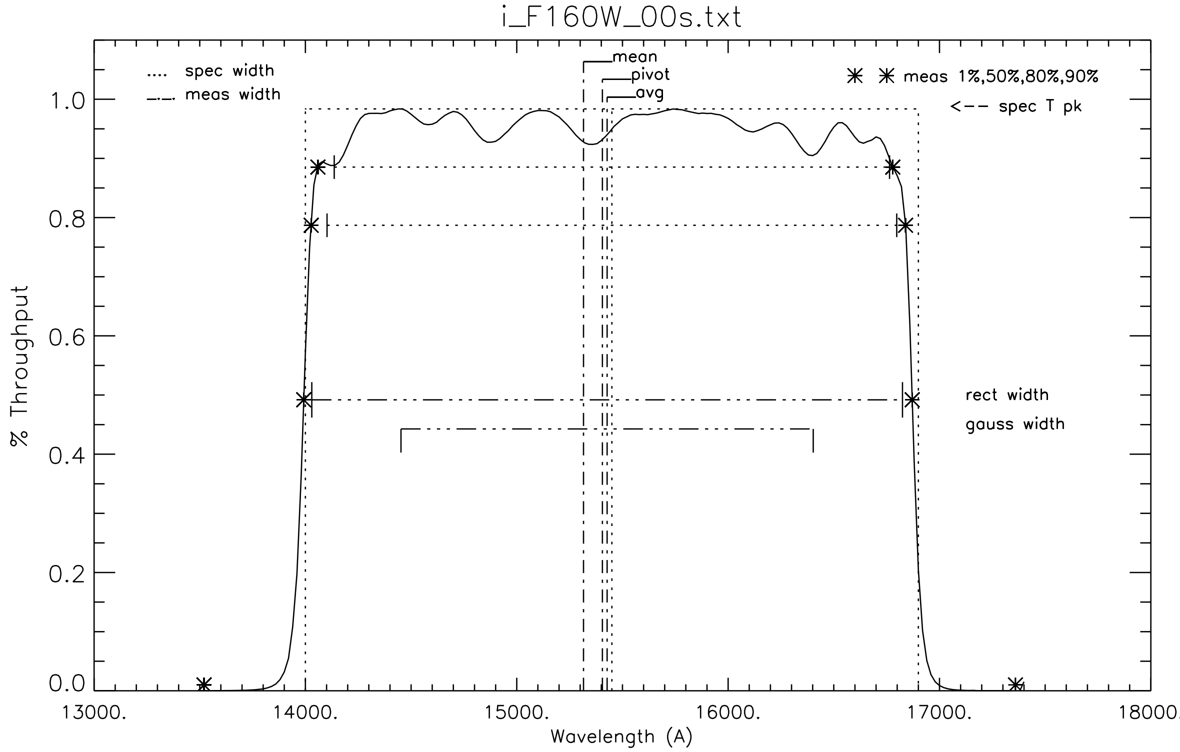


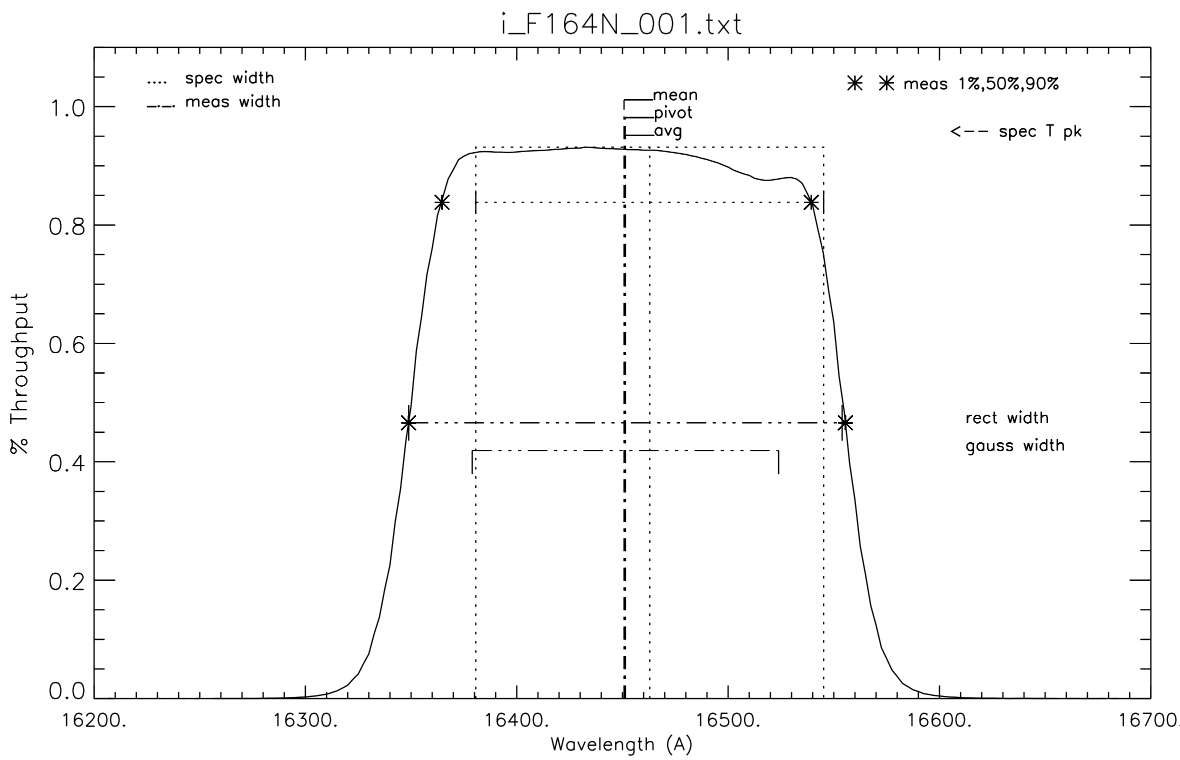
Panel 6: WFC3 IR Filters





Panel 7: WFC3 IR Filters





Panel 8: WFC3 IR Filters