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Wide Field Camera #3 Filter Selection Process - Part III- WFC3 IR Filter Requirements

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ABSTRACT

This is the third part of a series documenting the WFC3 filter selection and design program and this ISR describes the detailed requirements for the WFC3 IR Filters. In addition to documenting the specifications, we provide a high level introduction to filter design and manufacture. The WFC3 IR grisms are mentioned here but discussed in detail in another ISR (pending completion of those requirements).

1.0 Introduction to the WFC3 Filter Program

The Wide Field Camera 3 (WFC3) panchromatic capability makes it unique among HST instruments. The UVIS and IR filters span a large range of wavelengths.: 200nm - 1700nm. The UVIS channel houses 48 filter slots: 47 filters and 1 UV prism. Of those 47, 5 are quad filters providing additional bandpass capability. The WFPC1 Selectable Optical Filter Assembly (SOFA) is being re-used in the WFC3 and hence the thickness and dimensions of the UVIS filters are pre-constrained to fit within its slots. The IR channel single filter wheel contains 14 filters, 2 grisms, a clear hole and a blank slot. The IR and UVIS filter sets are shown schematically in Figures 1 and 2. These presentations clearly demonstrate the panchromatic advantages of this camera.
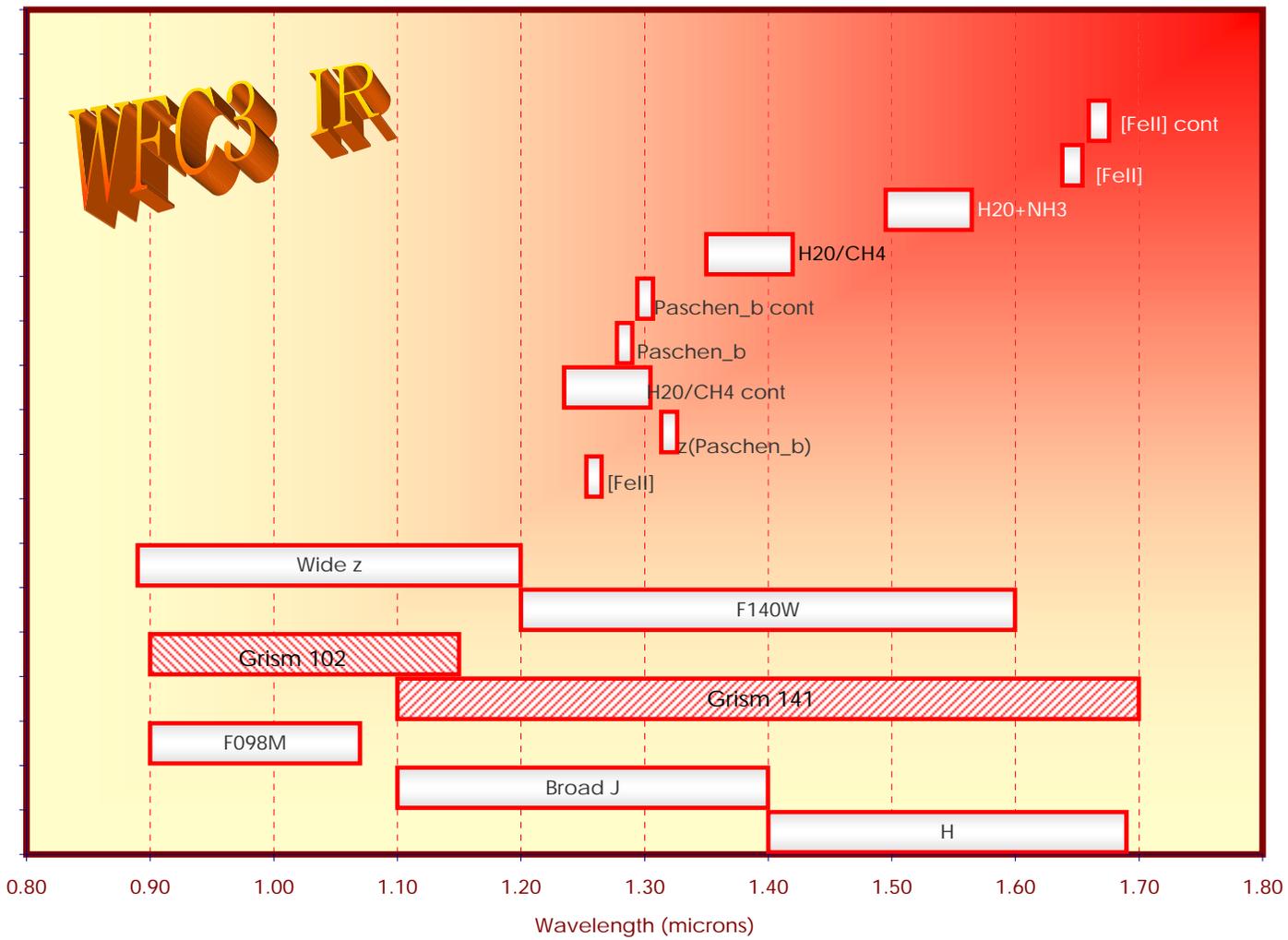
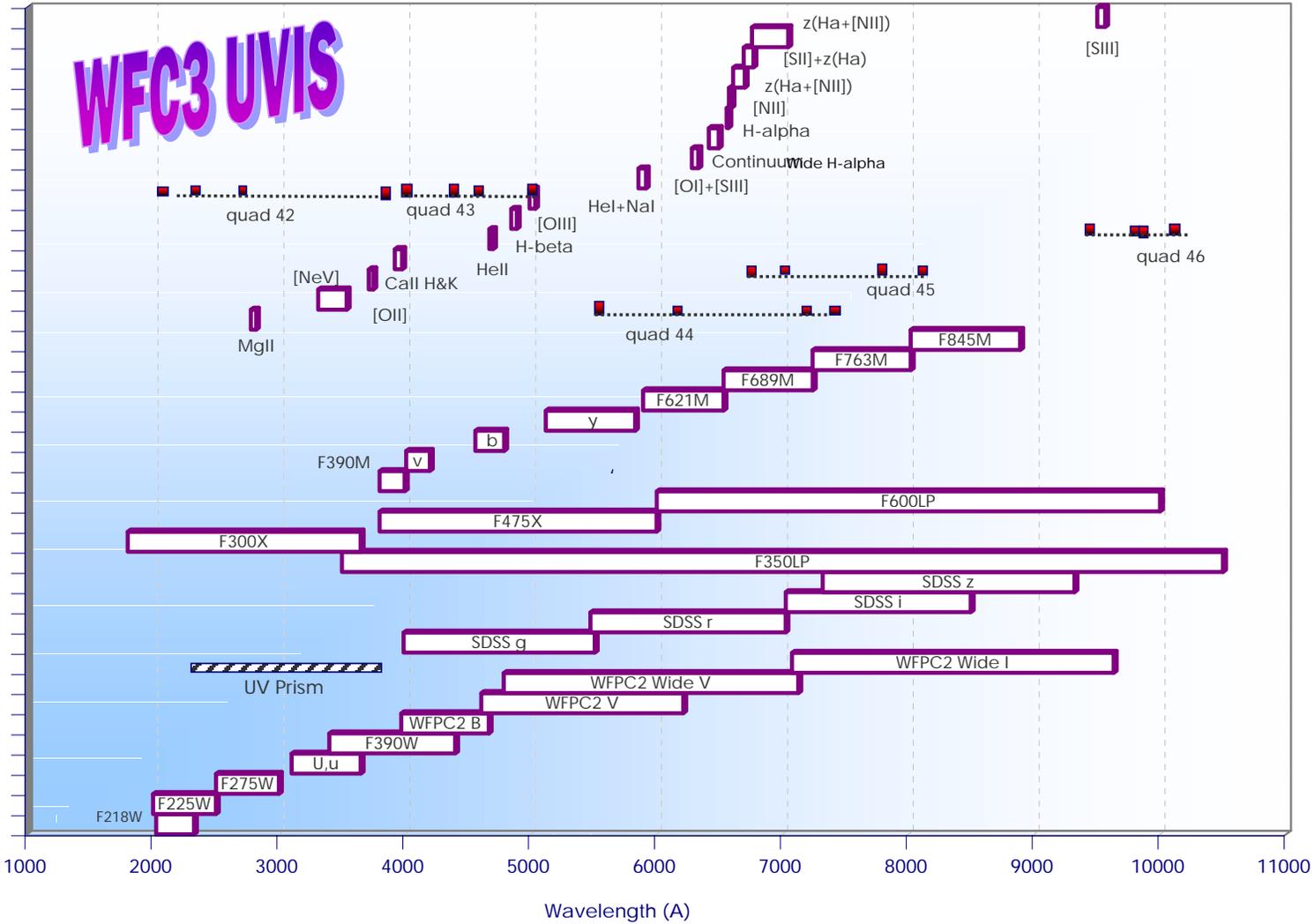**Figure 1: WFC3 IR Wavelength Coverage.** The length of the bars indicates the FWHM of the filter.

Figure 2: WFC3 UVIS Wavelength Coverage. The length of the bars indicates the FWHM of the filter.

1.1 Filter Program Collaborators

The WFC3 Scientific Oversight Committee (SOC) recommended a filter list to the WFC3 Science IPT (Integrated Product Team) and GSFC WFC3 Project. As described in Part II of this ISR series, the SOC received input from the astronomical community. The UVIS filter specifications document and procurement responsibilities are in the purview of JPL (J. Trauger and N. Raouf). The IR filter specifications and procurement are spearheaded by GSFC (R. Boucarut with support from O. Lupie-STScI). The filter characterization will be performed as a joint effort at Goddard and at the Jet Propulsion Laboratory.

1.2 IR Design Reference Mission

We encourage the reader to refer to the WFC3 Science White Paper (ed. Stiavelli, M. and O'Connell, R., 2000) for a comprehensive discussion of the science goals of the WFC3. The WFC3 Design Reference Mission document, a compendium of scientific programs proposed by the SOC members, was used to define the scientific goals and the flowdown to instrument performance requirements. The IR filters were selected to span the range between 0.8 and 1.7 microns, a region dominated by atmospheric absorption and emission from the ground. For example: very deep surveys of the faintest galaxies (high redshift) will be obtained in J and H; meteorological studies of planets searching for water vapor and methane will benefit greatly from the WFC3 IR channel because of the low scattered light backgrounds that hamper ground-based sites. Filters F139M and the line F127M (Water, CH_4) and F153M (Water and Ammonia) will be used for these studies. Infrared emission from the winds of newly forming stars in dense interstellar molecular clouds can be detected by looking for [FeII]1.64 micron emission (F164N). Figure 3 is a composite of a few examples of the types of science that can be performed with the UVIS and IR suite of WFC3 filters.
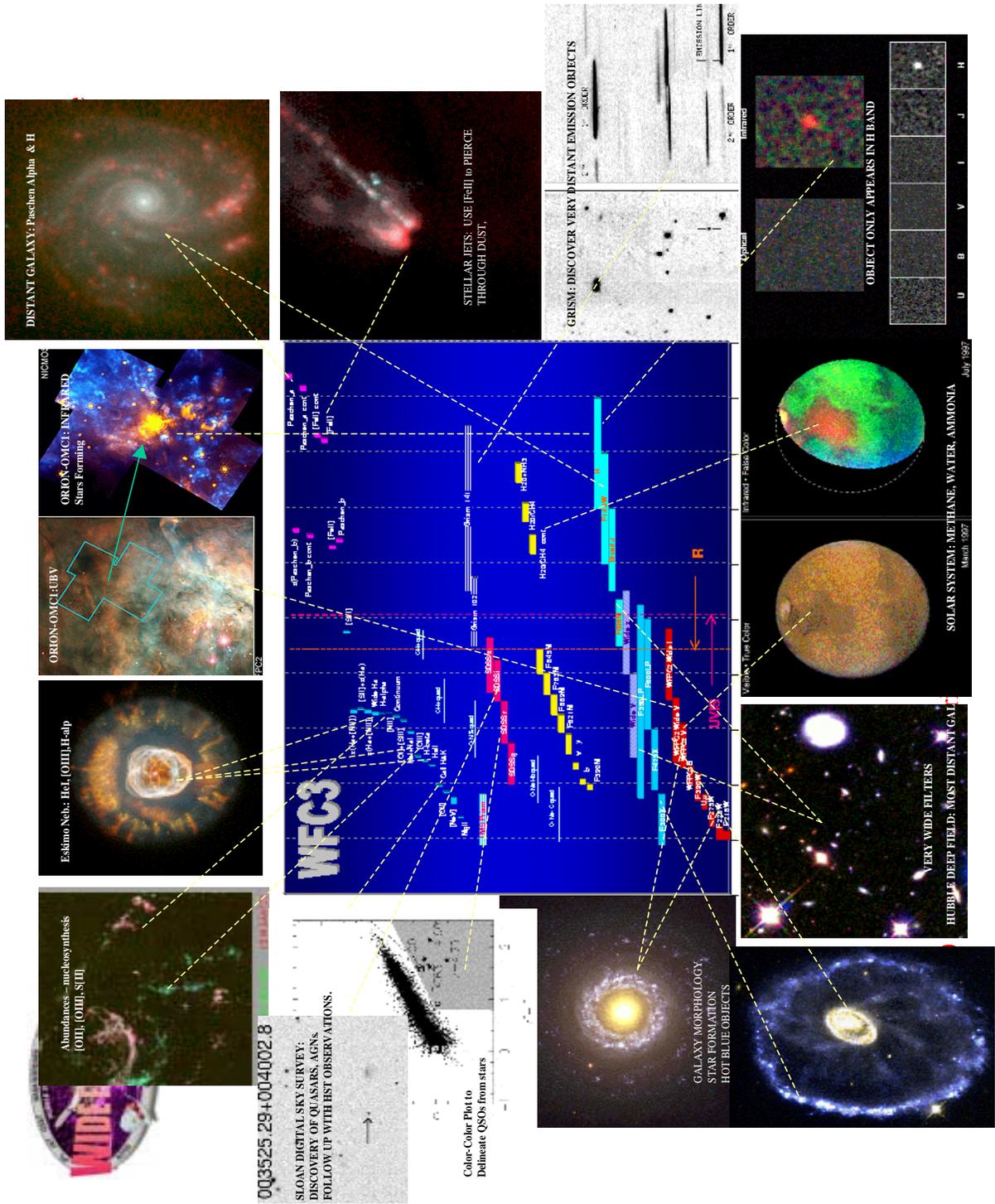
Figure 3: WFC3 Science: A composite science topics to be addressed by WFC3.

1.3 Filter Components and Manufacturing Advances
Thin-film optical filters consist of one or more substrates with coatings deposited on the surfaces to sculpt the bandpass and reject the out of band light. Interference filters consist of multiple layers of dielectric material having different indices of refraction. The interference that occurs between the incident and reflected waves at the thin-film boundaries and the transmission properties define the wavelength characteristic of the filter. Through the epoch of WFPC2 filter manufacture, the layers were applied by thermal evaporation in a vacuum, called *vapor deposition*. The quality and stability of the filter is dependent on the porosity of its microstructure. If moisture is accumulated in the coatings, the optical thickness of the coating changes, which causes a spectral shift in the bandpass. Further, a non-dense porous layer is not mechanically stable over long periods of time. As an example, a subset of WFPC2 spare narrow band filters, stored in a nitrogen purge over the past decade, have shown significant degradation around the edges, i.e., peeling and discoloration (Trauger, private communication). These narrow band filters were constructed using conventional evaporation techniques.

The lapse in the mechanical and chemical structure of the WFPC2 spare narrow band filters is most likely caused by a porous coating absorbing water. Minimization of porosity of the coatings and maximization of coating adherence and density are the goals of various deposition techniques. The kinetic energy of the atoms in the coating governs how well the coating adheres to the substrate: the higher the energy, the greater the surface mobility of the coating atoms and molecules and the more adherence and higher density of the coating. In conventional vapor deposition, energy is introduced into the growing film (so that it will adhere to the substrate) by heating the substrate. The new technology, *ion-assisted deposition,* has proven to enhance stability. The ion-assisted deposition process focusses a stream of ions onto a newly deposited coating layer. The transfer of energy from the ions to the surface atoms of the coating increases their kinetic energy and results in a packed, non-porous covering (which does not have to be subject to high temperatures). These dense layers contain much less water and contaminating materials. Ion-Assisted Deposition will be used for all the IR filters and all but 13 of the wide band UVIS filters.

1.4 A Note on Filter Theory and Design
A transmission interference filter is actually a Fabry-Perot etalon with spacings on the order of a few wavelengths. The filter itself consists of thin metallic layers with the spacings achieved using dielectric material. The optical properties of the filters can be expressed in terms of wavelength, thickness, index of refraction of the dielectric layers, angle of incidence, and the thickness, index and extinction coefficient of the metal coat-

ings. The coatings can also be described by the permittivity, permeability, and conductivity. Thin-film filters are designed on the basis of the solution of Maxwell's equations with the appropriate boundary conditions and values for the permittivity and permeability (both functions of wavelength) and the electric conductivity of the material. The index of refraction of the material is a function of these parameters. The basic theory may be reviewed in Macleod's *Thin Film Optical Filters* or in the paper "*Reflection and Transmission Interference Filters*, Part I. Theory" (Hadley and Dennison 1947). The calculations associated with several layers of multiple reflections in stratified media are conceptually acceptable but extremely cumbersome. Therefore, several software tools have been developed for manufacturers.

Macleod provides a simple qualitative description of how thin films work: 1) the reflectance of light at a boundary between two media is a function of the ratio of the indices of refraction at the boundary; 2) when the reflection occurs at a boundary of lower index, there is a phase shift of 180 degrees, and when the boundary is of higher index, the phase shift is 0 degrees; and 3) two beams, one reflected off a bottom interface and one off the top will recombine such that the beams interfere destructively (180 degree phase) or constructively (0 degree phase). A simple anti-reflectance coating is shown in Figure 4a and a complex Fabry-Perot filter with multiple reflections (similar to our filters) is reproduced in Figure 4b. The anti-reflection coating relies on complete destructive interference at each boundary. In the complex case of the Fabry-Perot filter, multiple beam interference in the spacer layer causes the transmission to be high over a narrow band of wavelengths. The interference condition relates the transmitted wavelength to the thickness and index of refraction of the spacer. If the spacer is a half wavelength ($k\lambda/2$, where k is an integer) of the desired central wavelength of the filter, other wavelengths will be attenuated by destructive interference. The calculation of the thickness of the spacer in a simple interference filter is given in equation (1) for normal incidence:

$$t = \lambda/(2n\cos\phi), \qquad\qquad (1)$$

where t is the spacer width, n the spacer index of refraction, and ϕ the angle in the spacer. For an angle of incidence (θ) other than 0 degrees, the central wavelength of the filter shifts blueward:

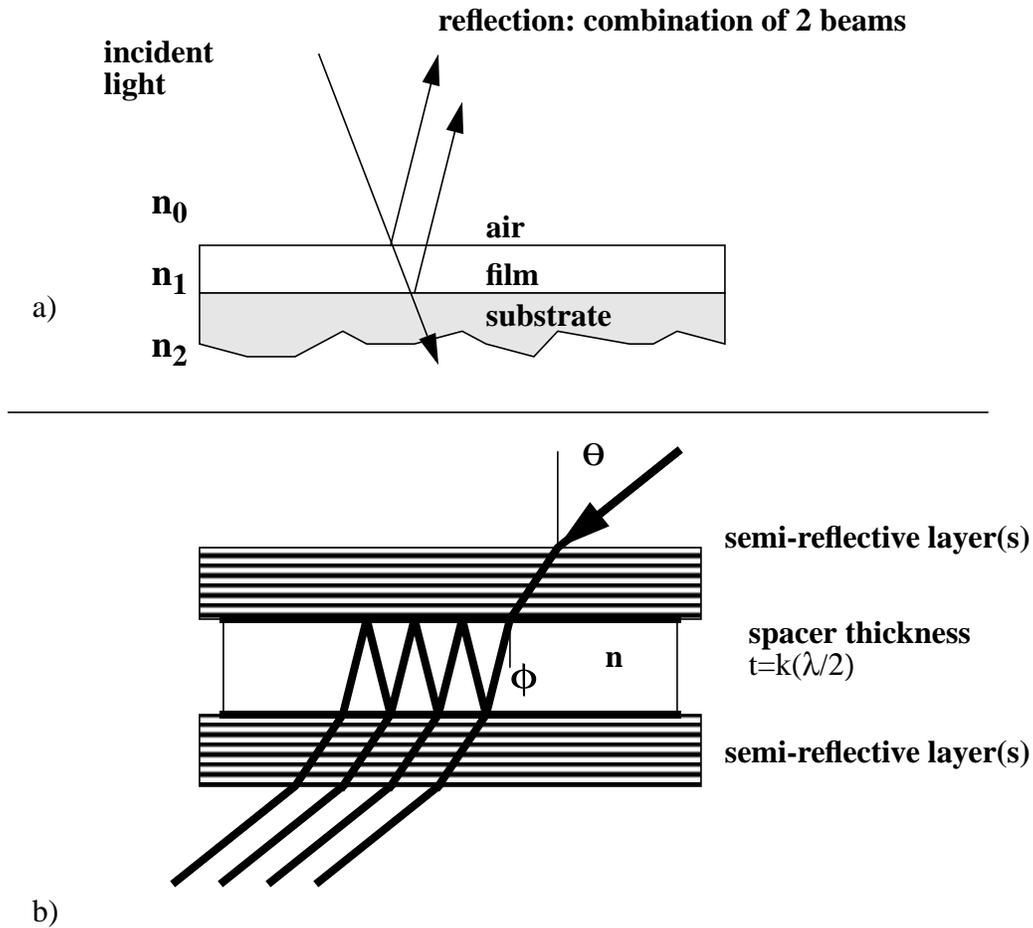$$\lambda = \lambda_c(1 - \sin^2\theta/n^2). \qquad\qquad (2)$$

Figure 4: **a) Simple single coating film. b) Multilayer interference filter**.

2.0 Descriptive Parameters

Several parameters are used to describe the details of a filter to a vendor. Many general characteristics such as central wavelength and FWHM are applied to all types of filters while some specific characteristics are needed for specialized filters, for example narrow band, short pass, long pass, quad, and ramp. Figure 5 illustrates the *basic parameters* which define a filter. The following definitions were adopted in our specifications to the vendors:

1. λ_{-50} and λ_{+50} are wavelengths on the blue and red side (of the central wavelength) where the transmittance equals 50% of the peak transmittance. For wide band filters, this wavelength pair specifies the FWHM. For narrow band, the 50% wave-

length pair is less important because the narrowband shape should be as rectangular as possible.

2. λ_{-90} and λ_{+90} define the region where the transmittance is greater than 90% of the peak. This pair along with the 1% points are critical for the specification of the narrow band filters. In the case of the broad band, the pair helps to specify the shape of the filter.

3. Central wavelength: The central wavelength is $\lambda_c = (\lambda_{-50}+\lambda_{+50})/2$. For the WFC3 narrow bands, the entire filter was shifted to the red by 500 km/sec. amounting to a shift of 0.00166 microns (much smaller than the width of the filter). This was done to extend the filter coverage toward the red (to accommodate redshifts).

4. Full Width Half Maximum (FWHM =$[\lambda_{-50}-\lambda_{+50}]$): The FWHM has higher scientific priority than the side slopes or the shape around the peak. The narrow band filters selected by the SOC were designed to have a width of ~10% the value of the central wavelength (unless otherwise compromised by interference from other lines or filters). Accompanying the narrow band filters are continuum filters whose FWHM are defined in the same way as the on-band counterparts, however their central wavelengths are not redshifted (or blueshifted) unless the need arises to avoid a spectroscopic feature.

5. Side Slopes: The shape of the passband is a function of the number of "cavities" in the design. The more cavities, the more *square* the filter. Unfortunately, a many-cavity design often results in more peaks and valleys in the transmittance. The tolerance on the shape can be specified as a slope of the filter sides. In some cases, contamination by neighboring astronomical features require asymmetric alteration of the shape of the filter. Consistency between the values and tolerances of the slope and the critical wavelengths is indeed important. The values for λ_{80}, $\lambda_{50,}$, $\lambda_{05,}$, and λ_{01}, are determined from the sloping sides of the transmission curves. Following the NICMOS example and comparing with NICMOS as-built filters, we adopted the following criteria:

   - Broad Band slope <=1.5% measured between λ_{80}, and, λ_{05}
   - Medium Band slope <=1% measured between λ_{80}, and, $\lambda_{05,}$
   - Narrow Band slope <=0.5-0.1% measured between λ_{90}, and, λ_{01}

6. Special Case Narrow Band Slopes: As an alternative for meeting the slope specifications for those narrow band filters with accompanying continuum filters, the mutually-shared overlap area of the line and continuum filters must be less than ~10%. The trade here is to minimize contamination by one filter into another and yet to make sure the separation is small enough such that redshifted lines are not missed. This special case is applied to the F128N and F130N and F164N and F167N pairs.

7. λ_{-01} and λ_{+01}: These are the wavelengths at which the transmittance is 1% (*absolute* as opposed to the r*elative transmittance with respect to the peak*). Beyond

either boundary, the transmittance must never exceed 1% absolute. Specifying the wavelength of the "absolute" flux is more convenient to the vendor, and for small peak transmittances, is easier to verify. Note that in the case of the WFC3 IR, most peak transmissions are well above 95% so that the absolute = relative transmission.

8. Ripple: Ripple is the descriptive term for the peaks and valleys which occur for several reasons, one of which is the number of cavities used to shape the filter bandpass. The more coatings, the more ripple. The tendency for rippling in IR filters is greater than in Optical filters. The IR requirements on ripple are: 1) the ripples stay constant with time, 2) they can be predicted from models of the filter, 3) they can be characterized on the ground, and 4) the ripple should not fall below 85% of the peak transmittance between the λ_{-90} and λ_{+90} critical wavelengths. The optical requirement, more easily achieved, is 90%.

9. Peak Transmittance T_{pk}: As the bandwidth narrows, the peak transmission usually decreases because more coats are needed to shape the bandpass and block the out-of-band light. UV filters have lower transmittance than ones in the visible and IR. Because the amount of out-of-band blocking decreases the peak transmittance, one must consider the trades between: blocking requirements, leak suppression, maximizing the peak, and minimizing the ripple in the wavelength structure.

10. Out-of-Band Transmittance (T_{OOB}): These specifications establish the blocking performance of the filter. The greater the blocking requirement, the lower the transmission efficiency of the filter. The blocking requirements are determined by considering the detector response, contamination by other emission/absorption lines or bands, and the trade between higher transmission efficiency and higher attenuation in the out-of- band wavelength regime. The dynamic range of the instrument can be limited by a poorly designed out of band transmittance requirement. The basic requirement is specified as an upper limit of the transmittance beyond the λ_{01} and λ_{+01} wavelengths. Typically, the vendors require specification of the wavelengths where the transmittance must not exceed a limiting value, such as 0.01% or 0.005%. Ripples out in these wings should not exceed these amplitudes. Another way to specify blocking is to determine how much area in the wings beyond the 1% wavelengths is tolerable for the photometric accuracy desired. See section on out-of-band rejection.
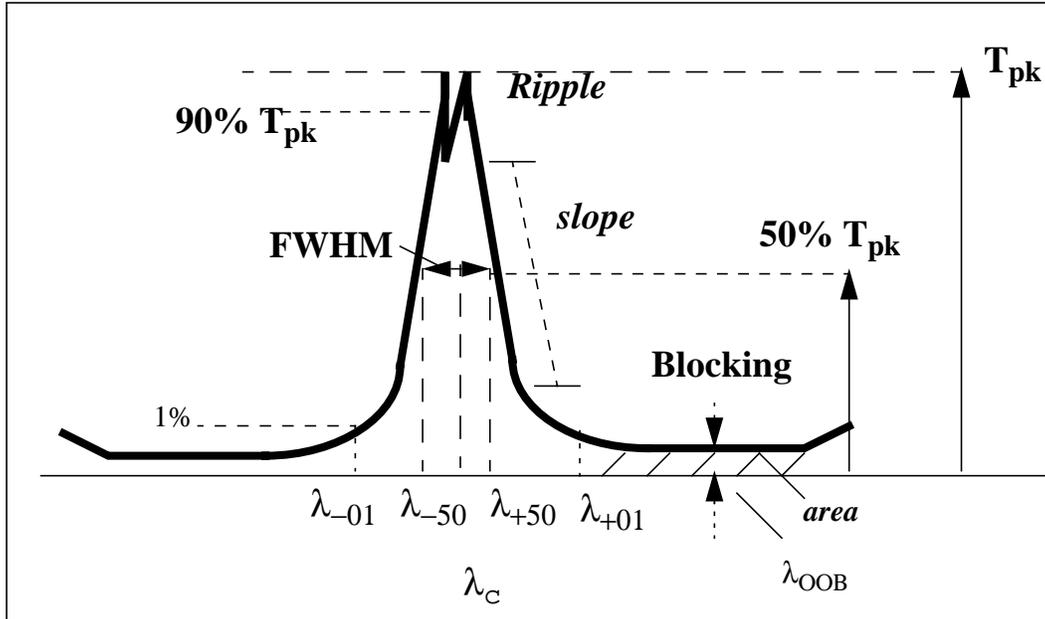
Figure 5: Illustration of a narrow band filter showing critical parameters.

3.0 Tolerances

The vendors are given the manufacturing tolerances on each parameter, the range of operational temperatures, and the maximum variability of the radiation environment. The tolerances were derived by considering the scientific requirements and the predicted instrument performance. The tighter the requirements on the filter however, the higher the cost and so consultation with the vendors is required to understand the compromises. Table 1 summarizes the critical wavelength tolerances for the categories of the IR filters in Angstroms.

Table 1. Tolerance Criteria for Critical Wavelengths

Critical Wavelengths	Tolerance Goal (Angstroms)	Tolerance Minimum (Angstroms)
Broad Band $\lambda_{-50}, \lambda_{+50}$	20	100
Medium Band: $\lambda_{-50}, \lambda_{+50}$	20	100
Narrow Band:		
$\lambda_{-01}, \lambda_{+01}$	5	20
$\lambda_{-90}, \lambda_{+90}$	5	20

4.0 WFC3 IR Filter Specifications

In Tables 2 and 3 are listed the basic specifications for the WFC3 IR Filters.
Table 2 describes the filter, its scientific priority as determined by the WFC3 Scientific Oversight Committee, and specifies the central wavelength and FWHM of the filter. The first two columns list the group priority and priority of the filter within that group. Note that the Paschen Alpha filters and the Wide V filter originally on the IR list were removed because a revised detector design precluded those wavelengths regimes. Columns 3 and 4 are the scientific equivalent and filter name. The central wavelength in air is listed in column 5 and the "adjusted" wavelength is listed in column 6. This adjustment accounts for a 500 km/sec redward shift of the central wavelength of the narrow band filters to accommodate a larger range in redshifted targets. Columns 7 and 8 are the same central wavelength information, but in vacuum. Columns 9 and 10 list the FWHM and $\%T_{PK}$. Columns 11 and 12 are the wavelengths at the 50% T_{PK}, and column 13 is the ratio of the filter width and central wavelength.

In Table 3, the description and filter name are listed in columns 1 and 2. Columns 3 through 6   are the central wavelength, FWHM, and $\%T_{PK}$.   Columns 7 through 14 are the transmittance at the key critical wavelengths. e.g., W-50 is the blue-side wavelength where the transmission efficiency is 50% T_{pk}. Columns 19 and 21 list the required attenuation, i.e., the upper limit of the transmission of light beyond the blue and red wavelengths listed in columns 20 and 22. The vendor often prefers an average value limiting the amplitude of leaks in the out-of-band region. A later section discusses in more detail the blocking specifications. Figure 5 illustrates the central wavelength, FWHM and range of the filters.
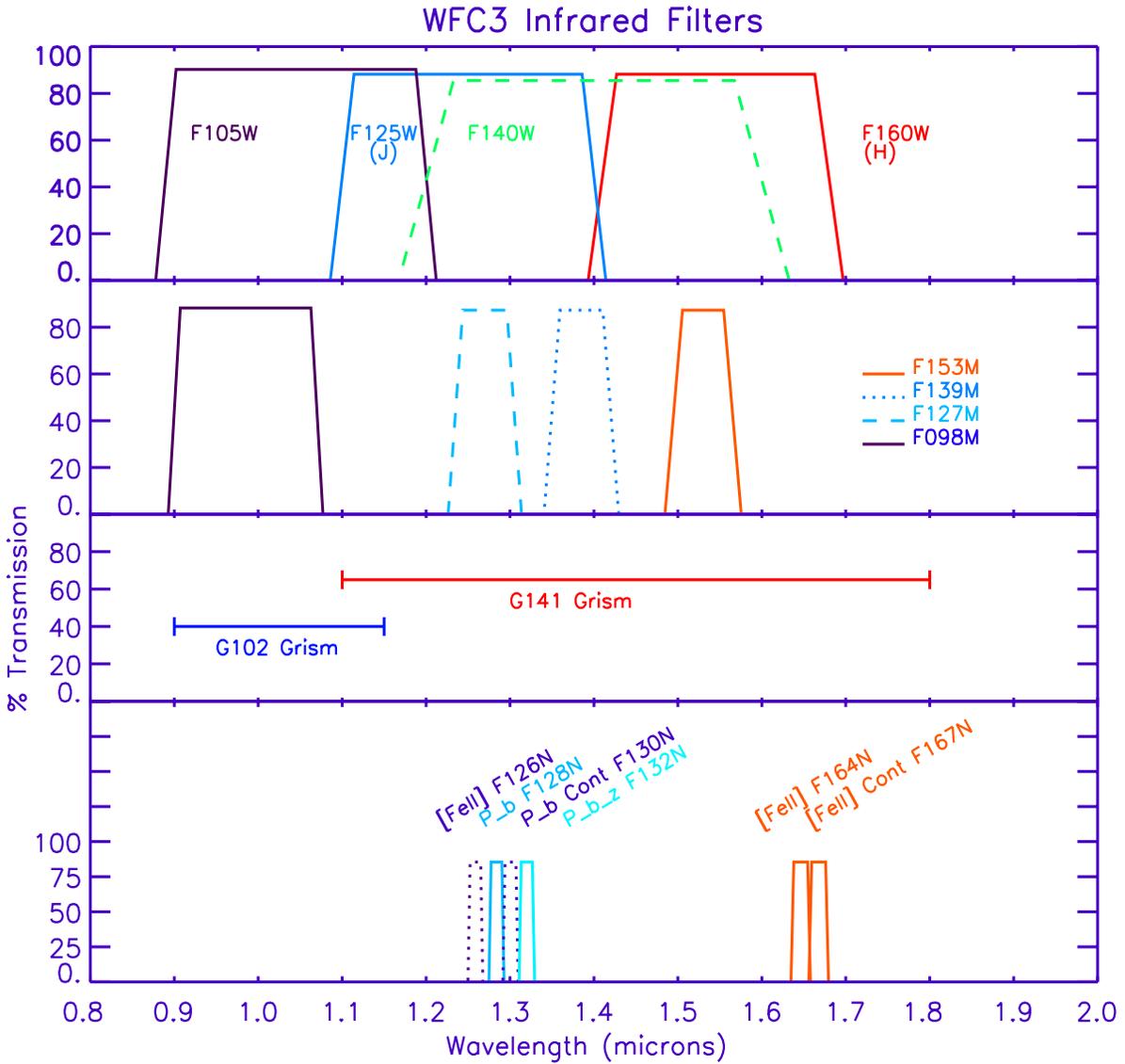
WFC3 IR Filters

Rev 10/13/00   Filter SPECS   "line in air" shift 500 km/se "line in vac" shift 500 km/sec

SOC IR Priority	#	Science Equivalent	Filter	AIR lam0 microns	AIR lamc microns central	Vac lam0 microns	Vac lamc microns	FWHM microns	%Tran	AIR Edge -50% pk microns	AIR Edge +50% pk microns	AIR del lam/ lam
group prio												
I	1	Broad H and Red Grism Ref *	F160W	1.54500	1.54500	1.545421	1.545421	0.290000	98	1.40000	1.69000	0.18770
I	2	Broad J	F125W	1.25000	1.25000	1.250341	1.250341	0.300000	98	1.10000	1.40000	0.24000
I	3	"Red" Low Resolution Grism	G141	1.41000	NA	NA	NA	0.600000	NA	1.10000	1.70000	0.42553
II	6	Water/CH_4 continuum	F127M	1.27000	1.27000	1.270346	1.270346	0.070000	98	1.23500	1.30500	0.05512
II	7	Water/CH_4 line	F139M	1.38500	1.38500	1.385378	1.385378	0.070000	98	1.35000	1.42000	0.05054
III	8	"Blue" High Resolution Grating	G102	1.02500	NA	NA	NA	0.250000	NA	0.90000	1.15000	0.24390
III	9	"Blue" Filter, Blue Grism Ref *	F098M	0.98500	0.98500	0.985269	0.985269	0.170000	98	0.90000	1.07000	0.17259
III	10	[FeII]	F164N	1.64355	1.64629	1.643997	1.646739	0.016463	95	1.63806	1.65452	0.01002
III	11	[FeII] continuum	F167N	1.66770	1.66770	1.668155	1.668155	0.016677	95	1.65936	1.67604	0.01000
IV	12	H_20 and NH_3	F153M	1.53000	1.53000	1.530417	1.530417	0.070000	95	1.49500	1.56500	0.04575
IV	13	Paschen Beta	F128N	1.28181	1.28395	1.282157	1.284296	0.012839	95	1.27753	1.29037	0.01002
IV	14	Paschen Beta continuum	F130N	1.30060	1.30060	1.300955	1.300955	0.013006	95	1.29410	1.30710	0.01000
V	15	[FeII]	F126N	1.25702	1.25912	1.257363	1.259460	0.012591	95	1.25282	1.26541	0.01002
V	16	Paschen Beta (redshifted)	F132N	1.32000	1.32000	1.320360	1.320360	0.013200	95	1.31340	1.32660	0.01000
NEW		Wide FAT "z"	F105W	1.04500	1.04500	1.045285	1.045285	0.310000	95	0.89000	1.20000	0.29665
NEW		Wide Band spanning J-H boundary	F140W	1.40000	1.40000	1.400382	1.400382	0.400000	95	1.20000	1.60000	0.28571
REMOVED		REMOVED										
II	4	Paschen Alpha	F187N	1.87510	1.87823	1.875612	1.878740	0.018800	95			
II	5	Paschen Alpha continuum	F184N	1.83500	1.83500	1.835500	1.835500	0.018400	95			
NEW		Wide V (UVIS Redundancy)	F065W	0.65000	0.65000	0.65018	0.65018	0.30000	98			

Table 2: WFC3 IR Filter Constants.

WFC3 IR Filters

Filter SPECS		shift 500 km/sec			AIR	AIR	AIR	AIR	AIR	AIR	AIR	AIR	AIR	AIR	AIR	AIR
		AIR			1	50	80	90	90	80	50	1				
Science		lamc	FWHM										Blue-side	Blue-Side	Red-side	Red-Side
Equivalent	Filter	microns	microns	%Tran	W-01	W-50	W-80	W-90	W+90	W+80	W+50	W+01	Attenuation	Max Wave	Attenuation	Max Wave
		central			microns	microns	microns	microns	microns	microns	microns	microns				
Broad H and Red Grism Ref *	F160W	1.54500	0.290000	98	1.38329	1.40000	1.41023	1.41364	1.67636	1.67977	1.69000	1.70671	1.00E-04	0.9820	5.00E-05	det cutoff)
Broad J	F125W	1.25000	0.300000	98	1.08616	1.10000	1.10848	1.11130	1.38870	1.39152	1.40000	1.41384	1.00E-04	0.9177	5.00E-05	1.5823
"Red" Low Resolution Grism	G141	1.41000	0.600000	NA	NA	NA	NA	NA	NA	NA	NA	NA				
Water/CH_4 continuum	F127M	1.27000	0.070000	98	1.22642	1.23500	1.24025	1.24200	1.29800	1.29975	1.30500	1.31358	5.00E-05	1.1744	5.00E-05	1.3656
Water/CH_4 line	F139M	1.38500	0.070000	98	1.34067	1.35000	1.35571	1.35762	1.41238	1.41429	1.42000	1.42933	5.00E-05	1.2966	5.00E-05	1.4734
"Blue" High Resolution Grating	G102	1.02500	0.250000	NA	NA	NA	NA	NA	NA	NA	NA	NA				
"Blue" Filter, Blue Grism Ref *	F098M	0.98500	0.170000	98	0.89290	0.90000	0.90431	0.90574	1.06426	1.06569	1.07000	1.07703	5.00E-05	0.8500	5.00E-05	1.1868
[FeII]	F164N	1.64629	0.016463	95	1.63477	1.63806	0.00000	1.63806	1.65452	0.00000	1.65452	1.65781	1.00E-05	1.6135	1.00E-05	1.6791
[FeII] continuum	F167N	1.66770	0.016677	95	1.65603	1.65936	0.00000	1.65936	1.67604	0.00000	1.67604	1.67937	1.00E-05	1.6345	1.00E-05	1.6995
H_20 and NH_3	F153M	1.53000	0.070000	95	1.48471	1.49500	1.50130	1.50340	1.55660	1.55870	1.56500	1.57529	5.00E-05	1.4409	5.00E-05	1.6190
Paschen Beta	F128N	1.28395	0.012839	95	1.27496	1.27753	0.00000	1.27753	1.29037	0.00000	1.29037	1.29293	1.00E-05	1.2593	1.00E-05	1.3086
Paschen Beta continuum	F130N	1.30060	0.013006	95	1.29150	1.29410	0.00000	1.29410	1.30710	0.00000	1.30710	1.30970	1.00E-05	1.2752	1.00E-05	1.3260
[FeII]	F126N	1.25912	0.012591	95	1.25030	1.25282	0.00000	1.25282	1.26541	0.00000	1.26541	1.26793	1.00E-05	1.2337	1.00E-05	1.2845
Paschen Beta (redshifted)	F132N	1.32000	0.013200	95	1.31076	1.31340	0.00000	1.31340	1.32660	0.00000	1.32660	1.32924	1.00E-05	1.2945	1.00E-05	1.3455
Wide FAT "z"	F105W	1.04500	0.310000	95	0.87810	0.89000	0.89727	0.89969	1.19031	1.19273	1.20000	1.21187	1.00E-04	0.8400	5.00E-05	1.3100
Wide Band spanning J-H bounda	F140W	1.40000	0.400000	95	1.16807	1.20000	1.21955	1.22607	1.57393	1.58045	1.60000	1.63193	1.00E-04	1.1100	5.00E-05	1.6900

Table 3: Critical Wavelengths and Blocking.

Figure 6: WFC3 IR Filter Set - illustration based on FWHM, central wavelength, and side-slope requirements.

5.0 Additional Filter Specifications

In addition to the wavelength dependence, there are several "physical characteristics" to be communicated to the vendors for proper manufacture of the filter. These include the substrate material, types of coatings, dimensions of the filter, how to mark the filter for

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proper placement in a wheel, the environment in which the filter will operate, the filter flatness and alignment, surface quality and others.

Operational Temperature: The filters must meet the requirements at the operating temperature of the instrument. In the case of the WFC3 IR the filters will be maintained at -30C degrees. The wavelength of the filter increases and decreases with changes in temperature according to a linear relation. The type of material used governs the filters ability to maintain integrity at temperature extremes. Laminated filters have a more limited temperature range because each component (glasses, cement, holders) has a different coefficient of expansion.

*Dimensions: A d*rawing of each type of filter is provided to the vendor to indicate the outer and inner diameter of the filters, whether the filters should *b*e parfocal and what specifications need to be met for this requirement. The drawings show the angle of incidence and the filter wedge tolerance. *An interesting note: the size of the filter and bandwidth often govern the cost and success probability of constructing the filter, e.g., very large-area filters are difficult because deposition processes may not be uniform over large areas, the stability of the coatings may be compromised and achieving very narrow band filters will be difficult.* Uniformity of performance across the filter is verified by uniformity mapping techniques (two dimensional interferograms) and also by aperture photometry. The resolution is established by the instrument beam size on the filter. Figure 7 compares the UVIS and IR filter and beam sizes and gives an example of an interferogram.

Wedge: In this context, the wedge specification determines the degree to which the filter surfaces are parallel, i.e., wedge is expressed as the angle between the surfaces. A complex filter with many layers and multiple substrates will probably not be as flat as a simple filter due to manufacturing issues. Non-parallel surfaces will result in a degraded image, displacement of the image on the detector, and possibly ghost images. Some astronomical investigations are sensitive to the relative motion of an image taken through multiple filters, e.g., high accuracy emission line color maps and extended object maps.   Shift and Add corrections in the image processing stage are difficult because of distortion and undersampling and therefore, photometric analysis on unregistered images will result in spurious features in the scene. Observational strategies such as dithering and drizzle can help compensate for image shift. In addition, filters can be rotated in their wheel slots during mounting such that the wedge effect nearly cancels. In the case of WFC3 IR filters, the wedge angle should not exceed ~10 arcsec - as mounted in the filter wheel. The corresponding image displacement is ~ 0.5 IR pixels, an acceptable value taking into account the additional corrective measures. This amount of wedge contributes no more than 0.002 waves of Transmission Wavefront Error (TWE) to the image quality budget. At the dis-

tance of the filter to the focal plane, the adopted wedge requirement will result in distortion that is much smaller than the beam size on the filter.

The physical dimensions and wedge specs are given in Table 4, as extracted from the Ball SER OPT-011 (Turner-Valle 1999).

Parameter	Value
Filter Diameter	25.4mm (circular)
Distance: Filter Wheel to Focal Plane	123.488mm
Thickness	4.0+/-0.1mm fused silica (or equivalent for parfocality)
Clear Aperture (unvignetted area)	22 mm (circular)
Wedge	<10 arcsec
Transmitted Wavefront over sub aperture	over 14mm, filter < 0.02waves at 6328A
F# and Angle of Incidence of light cone on filter	F/11, +/-4.6 o

Table 4: IR Filter Dimensions and Wedge Specifications.

Parfocality: The filter substrate thicknesses must all be matched so that the instrument focus remains at one optimum F_{shift} for all filters. This condition precludes the undesirable operational need to refocus the camera with each change in filter. The substrate/blocker/epoxy - together must match the criteria. For example, the focal shift F_{shift} for a multiple-substrate filter is the sum of the shifts from each substrate layer and epoxy as expressed in equation (3).

$$F_{shift} = t_1 (n_1-1)/n_1 + t_2(n_2-1)/n_2 +.... \qquad (3)$$

Angle of Incidence: The vendor needs to know the angle of incidence and tolerance on that angle for achieving the focus criteria. The IR channel beam size is F/11 which produces a beam width at the filter wheel of +/-4.6 degrees over the full field of view.

Scratches and surface roughness: Physical examination of the filter surfaces (initially by eye) is an easy and surprisingly valuable assessment of the quality of the filter surfaces. From experience, optical engineers set the upper limit on pits, scratches, and irregularities to < 3 nm.

Coating Quality: The coating quality criteria applies to the substrates, coatings, and anti-reflection coatings. Visual Quality is one of the initial quality assurance tests to make. For

the IR filters, the requirement to be met is that no non-uniform structures or scratches can exceed 40-20 per MIL-0-13830 with the unaided eye. Hardness, Adhesion, and Humidity are also tested and the requirement is no evidence of visible deterioration, erosion, or pitting.

Anti Reflection Coatings: To minimize stray light, the IR filters will be coated with an anti-reflection coating. The reflectance of the coating must not exceed 1% in the bandpass of the filter. This coating does not define the bandpass in any way.

Transmitted Wavefront: To insure that the IR filters transmit quality images, an upper limit is set for the transmitted wavefront error and is based on the total optical performance budget. For both the IR and UVIS filters, the transmitted wavefront error from the filters must not exceed 0.02 waves (rms) at 6330A over a throw of 12mm. The IR filters are 25.4mm in diameter. The transmitted wavefront error will be measured at the central wavelength of the filter.

Birefringence and Scattered Light: Loss of efficiency will occur if the filter is birefringent, i.e., the filter polarizes light as a function of wavelength. Scattered light also results in losses in throughput and could also result in contamination of observations. Filters are viewed through cross-polarizers to assess the birefringence. The scattered light requirement is also provided to the vendors, e.g., the Bidirectional Transmission Distribution Function (BTDF) shall not exceed 1/steradian at a deviation angle of 5 degrees.

Other Proper Specifications: The optical engineer needs to know how to insert the filters into the filter wheel: which filter is which, which is up/down, right/left (if it matters), which way residual wedge is tilted (e.g., so that the J and H filters can be mounted to minimize the shifting of an image between them). The type of labelling, location of the label and an agreement on the syntax of the labelling must be well understood in advance. The requirements also include specifications of the substrate material, types of bonding methods and adhesives, and edge sealant materials
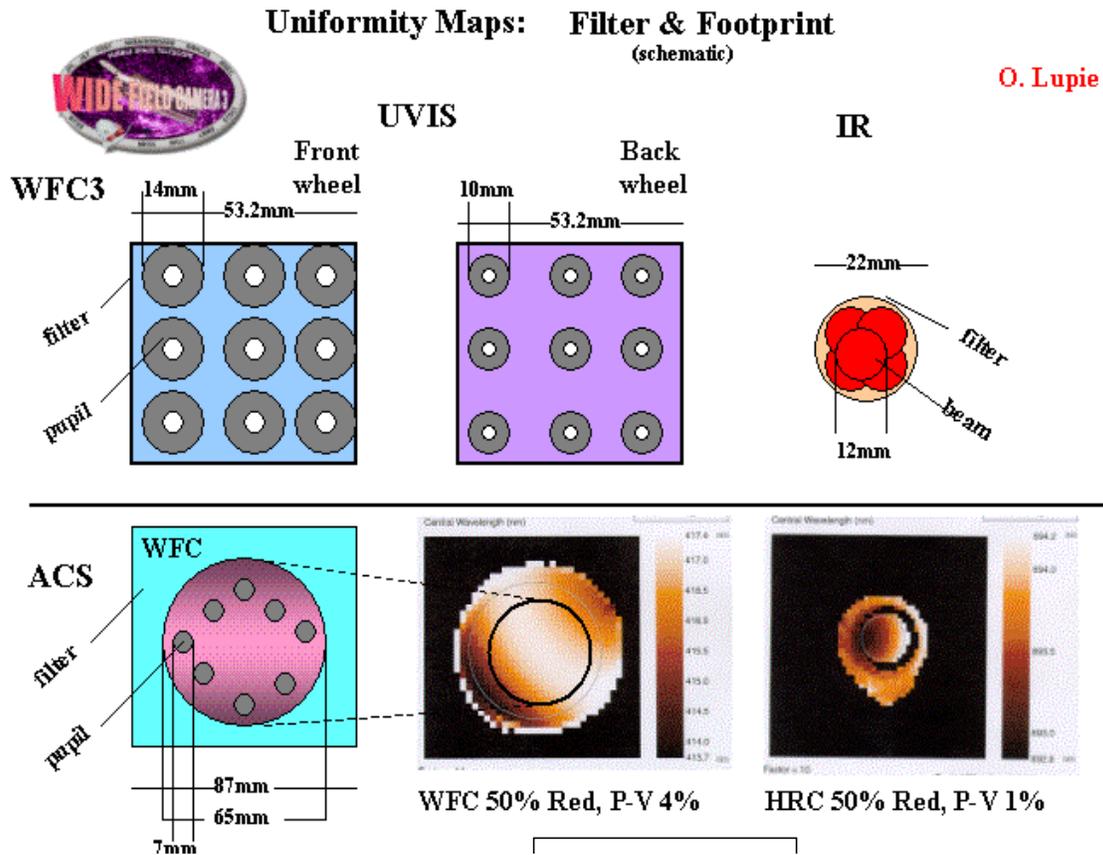
Figure 7: Comparison of the Filter Sizes and Beam Sizes: WFC3 UVIS and IR.

Environmental Requirements: The filters must maintain their integrity during all phases of the process from lab testing, through launch, through the orbital environment. Table 5 lists the various environments and requirements.

Table 5: Environmental Requirements from testing through in-orbit operation.

Environment	Value
Acceptance Test	
Temperature	20+/-5C
Humidity	<40%RH
Storage	
Temperature	-20C to +40C
Humidity	<40%RH

Environment	Value
Launch Shuttle	
Temperature	-20C to +40C
Humidity	0 to 50% RH
Pressure	15psi to 10-06 Torr
Vibration	7.9G RMS
In-Orbit	
Operating Temperature	0+/-5C
Survival Temp Range	-20C to +40C
Pressure	<10-06 Torr
Particle Radiation	5.0e-03 rad

6.0 Filter Notes

In this section, design notes and comments for each filter are documented. We refer the reader to Table 2 for a priority ranking of the IR filters from the scientific perspective. Figures 8 and 9, derived from the FWHM, central wavelength, and side slopes, are high resolution illustrations of the IR filters.

F160W Broad H (and red grism reference): This highest priority filter will be used for many different astronomical studies, e.g., deep images of the highest redshift objects. Originally, the "nominal" H filter design duplicated that of the NICMOS F160W filter. Since that time, the red detector cutoff has been changed from > 1.8 μ to ~1.7 μ. Because the exact red cutoff is not known at this time and the photometric requirement dictates that the filter throughput cuts off within the bounds of the detector sensitivity, two H filters will be manufactured., each with different red cutoff profiles. The selection of the flight filter will come later when the filter wheel must be populated and when more information on the detector characteristics are available.

F125W Broad J: The J filter holds the second highest scientific priority. The filter design is similar to the ground based J for ease of photometric transformation. Therefore, even if the H filter design narrows to accommodate a shortened red detector cutoff, the J filter will remain constant in central wavelength and area.

F140W: This filter is specifically designed to bridge the gap between the J and H filters so that continuous near-IR wavelength coverage can be offered to the astronomical community.

F105W ('*Fat' z*): This is a wide Sloan-like z filter. The FWHM is 0.3 μ and is shifted to the red of its original design (by ~ 600A) in order to accommodate a detector blue cutoff of > 0.85 μ. The 50% critical points fall at 0.89 and 1.2 μ (Frogel and Windhorst, email 7/2000).

F139M [line] and F127M [continuum]: The water and CH4 band lies between 1.35 and 1.42 μ and the continuum region between 1.22 and 1.32 μ (Marley and Young). Both line and continuum filters have a bandwidth of 700 μ. The F139 μ pair was selected over the stronger band at 1.72 μ because of the uncertainty of the detector red cutoff. Maintaining a photometric accuracy of ~1-2% in an environment where the detector sensitivity (and possibly its red cutoff) could change with time requires that the wavelength dependence of the filter throughput be stable with time and well defined.

F153M [line]: The water+ammonia band is centered at 1.53 μ.

F098M (blue grism reference): The filter is specifically designed for wavelength coverage between 0.9 μ to the J filter. It will serve as the 102 grism reference filter and it is also carefully designed to compliment the WFC3 UVIS filter, F845M, whose red 50% critical wavelength is ~0.9 μ. The overlap allows coverage over a continuous wavelength range for certain studies such as objects of redshift z > 7 exhibiting lyman alpha dropouts (Frogel and Windhorst, email 7/2000).

F164N ([FeII] line) and F167N (continuum): The 1.64 μ line filter was designed to minimize contamination from the HI Brackett 12 line at 1.6401 μ. The narrow band filter widths are 10% of their central wavelengths. The central wavelength of F164N has been shifted to the red by 500 km/sec to increase the redshift range. The NICMOS contains a similar set of filters however the continuum filter is centered blueward of the WFC3 continuum. Finally, the line and continuum filters are separated in wavelength such that there is less than 10% overlap relative to the area of the filter. Figure 10 compares the WFC3 with the NICMOS 164N filter. The slanted numbers in the upper part of the diagram refer to the velocities sampled by the filter with 0 km/sec at the [FeII] line center (air).

F128N (Paschen Beta) and F130130N (Continuum): The Paschen Beta line and continuum filters were designed to minimize the contamination from 12869A+12784A H_2 and

12784A He I. The filter widths are ~10% of their central wavelengths. The central wavelength of F128N has been shifted to the red by 500 km/sec to increase the redshift range.

F132N (Paschen Beta Redshifted): The redshifted version of the Paschen Beta F128N filter will provide redshift coverage out past the Coma cluster, z~0.03. The F130N filter can be used as the continuum for this filter.

F126N ([FeII] line): This narrow band filter will be used for reddening studies along with the F164N [FeII] filter. It is similar in design to the F164N filter with the 500 km/sec wavelength shift to the red. WFC3 has a few narrow band filters that can be used as the continuum filter for F126N such as F130N. The line was designed to minimize contamination from 12529A He and 12618A H_2 triplet.
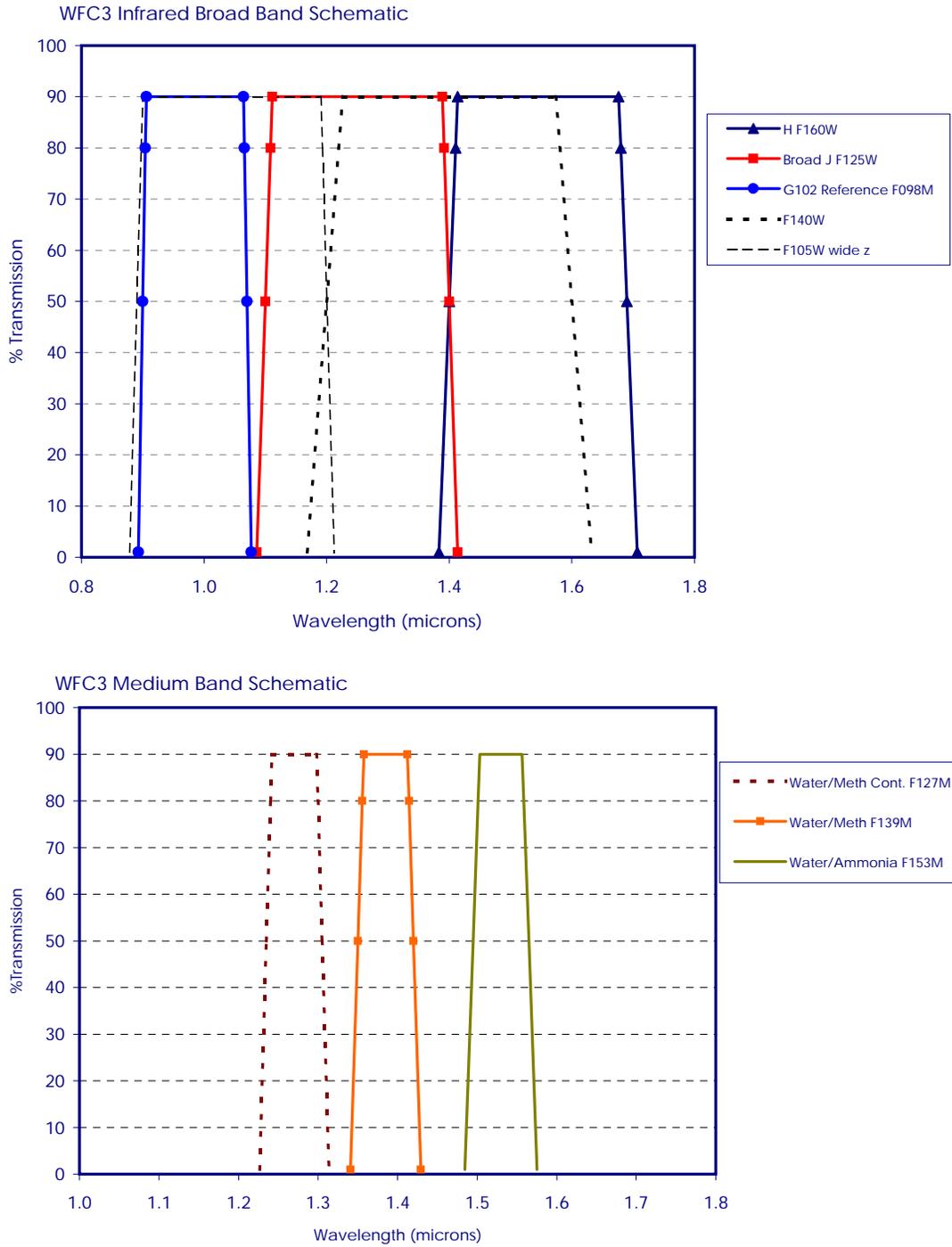
Figure 8: Comparison of the WFC3 IR broad and medium band filters. Illustrations are based on specified FWHM, central wavelength, and side slopes.
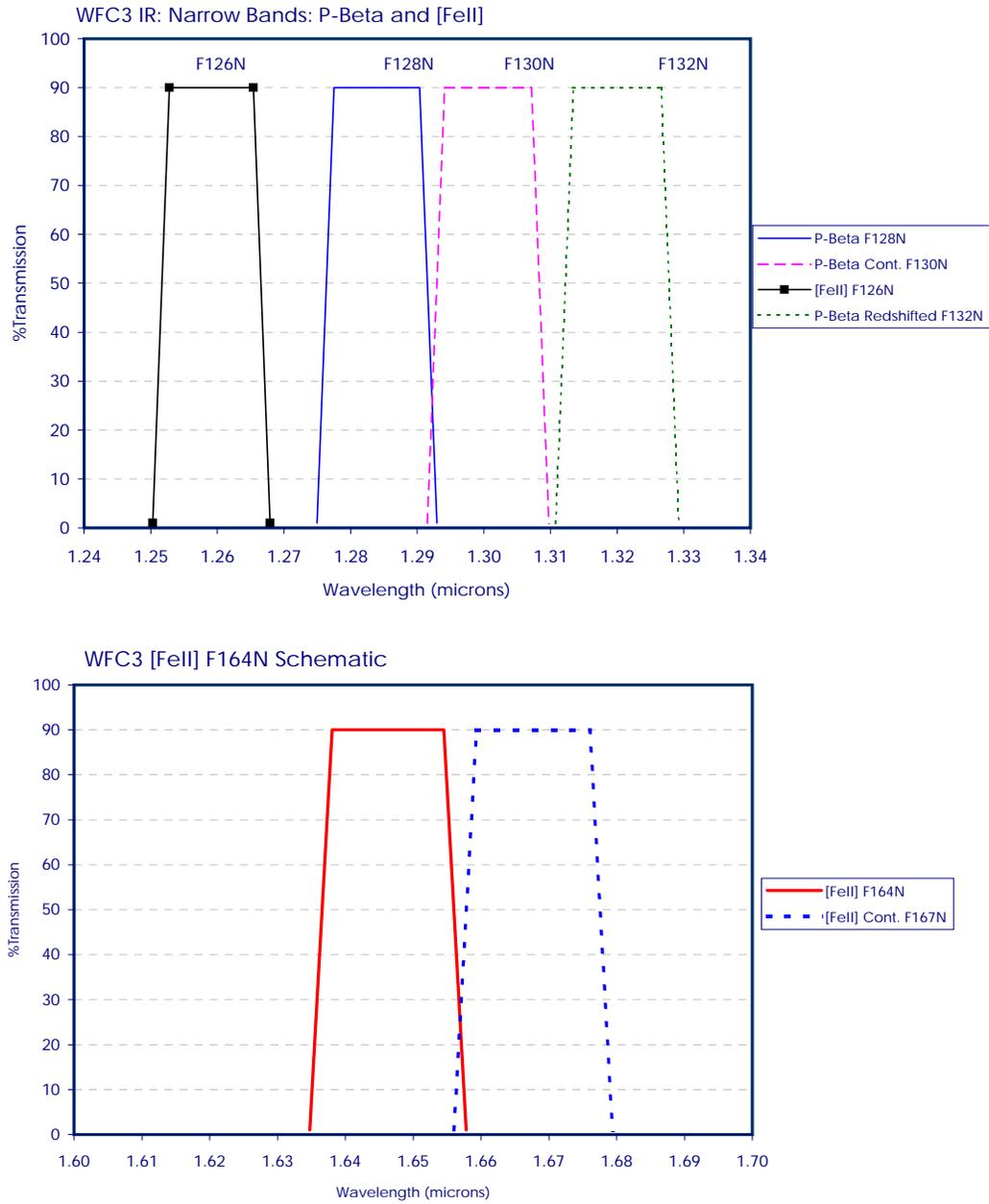
Figure 9: Comparison of the WFC3 IR narrow band filters. Illustrations are based on specified FWHM, central wavelength, and side slopes.
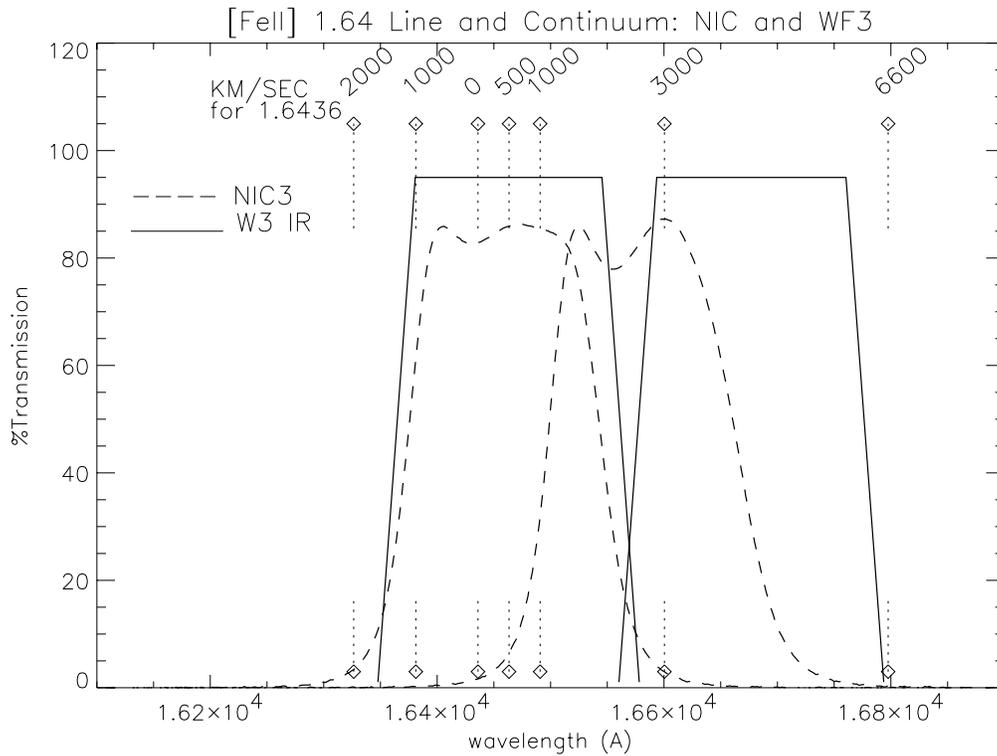
Figure 10: WFC3 [FeII] line and continuum compared with NIC3 [FeII] at 1.64 microns. Note that the rest wavelength and the WFC3 line center are shifted by 500 km/ sec. The slanted numbers at the top of the figure are the associated velocities in km/sec.

7.0 Discussion of Out of Band Blocking

The filters are manufactured with multiple blocking coatings which suppress light on either side of the bandpass. The extent to which the out of band light is blocked depends on the number of cavities, the overall design, how much of the peak transmission one is willing to accept. We adopted a method to directly relate the out of band blocking requirements to the scientific requirements:

1. the total light within the area bounded by the wavelengths at 1% and ~10e-5 of the peak transmittance must not exceed a certain percentage of the total area sampled by the in-band transmittance. To achieve a few percent photometry within the band, limiting the spurious out of band transmittance to < 1% is in order, i.e., a goal of a few tenths of a percent.

2. ripple amplitudes in the out of band wings must not exceed a specified value. This requirement prevents the possibility of a large ripple coincident with a neighboring emission or absorption line.

3. The ripple structure from 1% and outward (toward the blue and red) must be understood via modelling and verified on the ground. Knowledge of the filter transmission structure is key to in-flight calibration. The manufacturer's experience indicates that the ripple structure remains very constant with time.

Without performing actual filter structure modelling, the shapes of the actual transmission at the base of the filter and out in the wings were not exactly known to us. The overall filter structure is better described as a voigt profile, however, the wings can be treated as gaussian in shape. We structured the base and wings in two different ways: a gaussian fall off and a worst case linear fall off between the 1% wavelength and the 10e-5 wavelength. The area between the 1% wavelength and the 10e-05 wavelength was compared to the area of the in-band region. As a result, we chose the out-of-band cutoff wavelength to be such that the area between 1% and 10-05 was <1% the area of the rest of the filter. The values are given in Tables 2 and 3. An example of the procedure is illustrated in Figures 11 and 12.

Our initial out of band requirements gave enough information to the vendors to determine feasibility (and cost) and inputs to their models. A more accurate assessment of the out of band characteristics of the filter is possible using actual models of the filter coatings, especially if rippling is the characteristic in the wings. The next stage of filter design is for the vendors to produce the actual model filter transmittance curves and work with the customer to make sure that the out of band blocking is adequate. An ISR report on this stage of the procedure is pending delivery of the models by the vendors.
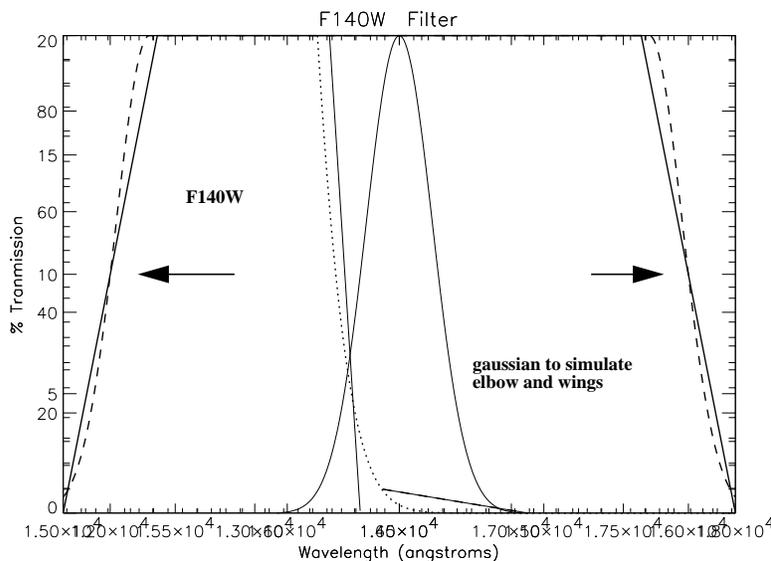
Figure 11: Model of Base and Wings: broad band filter F140W (solid outer lines), and the gaussian used to model the elbow and wings of the filter.
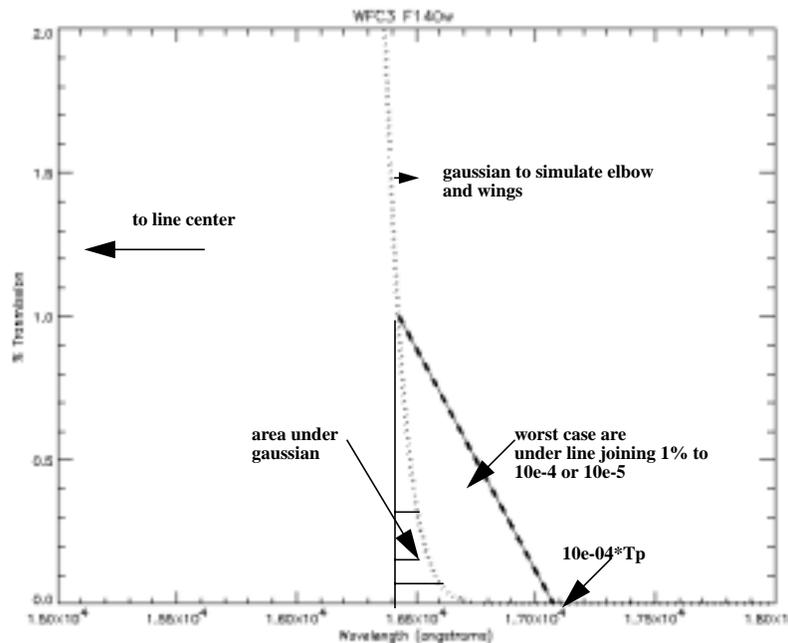
Figure 15: Expanded view of the gaussian elbow and the worst case linear shape between the 1% wavelength and the Out of Band Cutoff wavelength.

ACKNOWLEDGEMENTS:

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APPENDIX: Comparison with NICMOS

For ease of comparison, the WFC3 Broad and Medium band filters are plotted with the corresponding NICMOS filters in Figures A1 and A2. The narrow band and spectral elements included in both instruments are: [FeII] 1.64µ and continuum (NIC1), and grisms Grism G141 (NIC3) and Grism G96 (NIC3).
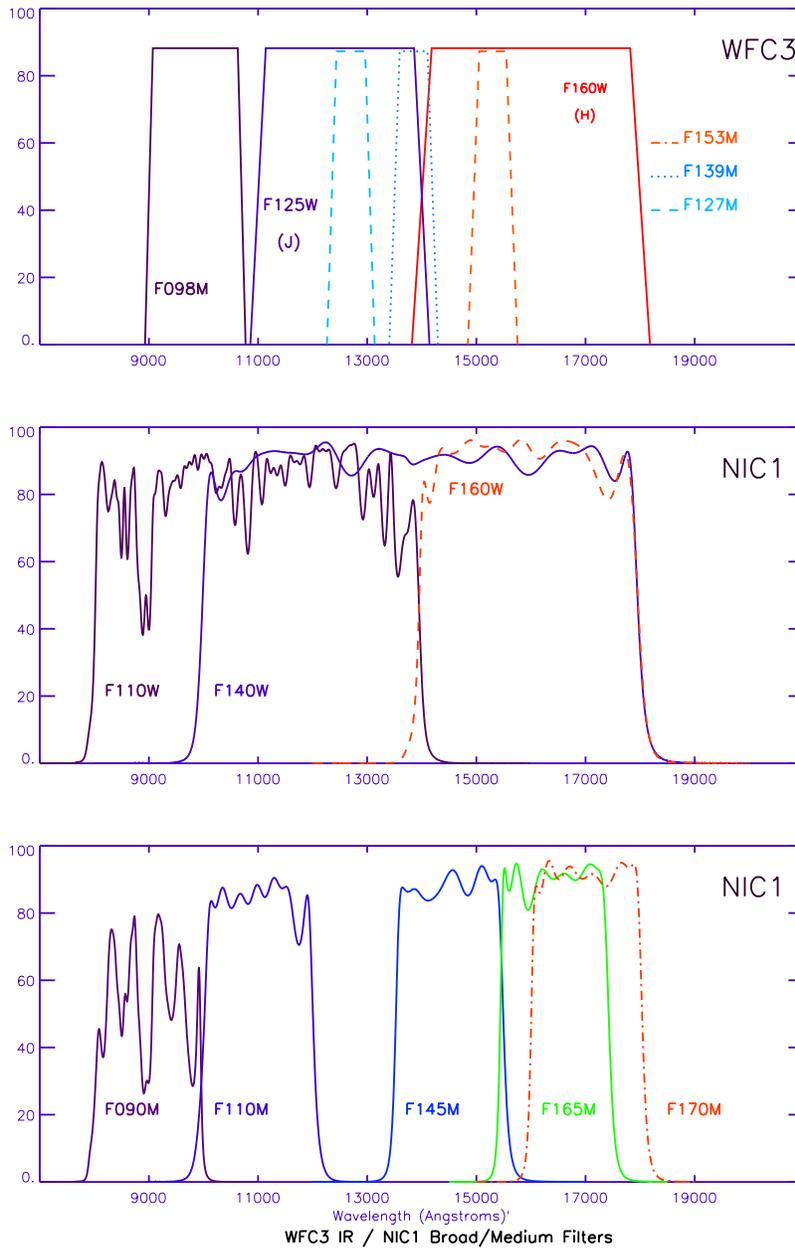
Figure A1: T**he WFC3 Broad and Medium Bands compared to NIC1**.
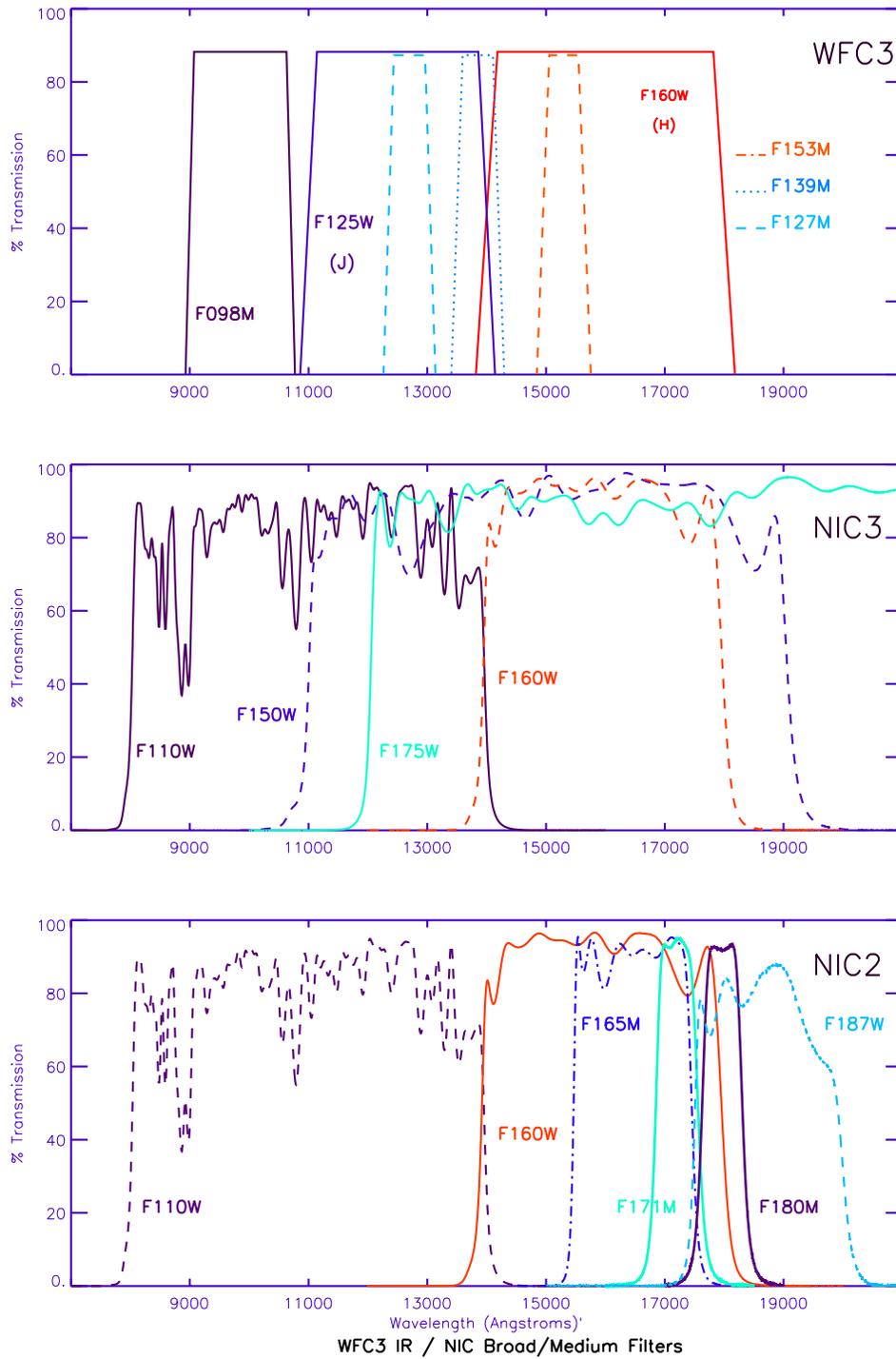
Figure A2: The WFC3 Broad and Medium Bands compared to NIC2 and NIC3.