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**Instrument Science Report WFC3-2000-007**

# Wide Field Camera 3 Filter Selection Process - Part I: HST Historical Filter Usage

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April 12, 2000

**ABSTRACT**

*For the sake of historical documentation and preservation of the logic behind the selection of the suite of WFC3 filters, this series of four reports presents a summary of the selection process and the final filter lists. Part I introduces the instrument and provides relevant studies of historical HST filter usage. Part II provides a brief synopsis of the WFC3 Filter Workshop during which the astronomical community responded to the solicitation of their inputs. Parts III and IV present the IR and UVIS filter specifications, define filter terms, and compare the suite of WFC3 filters to the those of NICMOS, ACS, and WFPC2.*

## 1. Introduction

The WFC3 project is unique in the experience of HST for the following reasons, all of which have some influence on the filter selection process:

1. rather than targeting specific key programs, the emphasis is on maximizing scientific capability over broad areas of astronomy;
2. the instrument is being designed, developed, and tested by an "internal" consortium, GSFC, STScI, Ball, (and a small number of other subcontractors) rather than using the services of an Instrument Definition Team;
3. a voluntary team of astronomers with a wide range of scientific expertise, called the Scientific Oversight Committee (SOC), provides science guidance to the WFC3 project. The SOC is considered the voice of the astronomical community and is charged with advising the WFC3 team in all areas of instrument design, operation, and capability.

The filter lists are comprehensive and cover a broad selection of scientific topics. The goal of this series of reports is to document the WFC3 Filter Selection Process and thus to preserve the logic behind the selection and design of the WFC3 filters, a major charge of the SOC and the Science IPT. To support the SOC in its advisory capacity with respect to filter selection, the SOC was presented with background information and tools:

- a study of historical HST filter usage of the imagers: FOC, WFPC1, WFPC2, and the STIS image modes.
- a special filter workshop at the STScI where community astronomers discussed their filter priorities in several areas of astronomy, and
- an Exposure Time Calculator for the WFC3 that can be used to aid in filter design and in post-fabrication performance assessment.

Part I documents relevant studies of historical HST filter usage; Part II provides a brief synopsis of the WFC3 Filter Workshop where invited and volunteer members of the astronomical community responded to the solicitation of their inputs.; Parts III and IV present the final IR and UVIS filter lists and specifications, and compare the suite of WFC3 filters to the those of ACS, STIS, NICMOS and WFPC2.

## 2. Introduction to WFC3

Before embarking on a brief technical description of the WFC3 camera, an overall comparison of relevant attributes to those of other HST instruments is provided in this section. The WFC3 features two independent optical chains, referred to as the UVIS and the IR channels.

### *2.1 Comparison to WFPC2, ACS and STIS*

The following is a description of the UV and visible capabilities of WFC3, ACS, STIS, and WFPC2:

1. The WFC3 UVIS channel emphasizes the UV sensitivity [2000-4000A] over a large field of view, 160 square arcsec with 39 milliarcsec pixels. In contrast,

   - the WFPC2 has low blue sensitivity and a large FOV (150x150 arcsec).
   - the ACS HRC has similar blue throughput as WFC3 (7x higher than WFPC2), but a much smaller FOV of 25 square arcsec.
   - STIS imaging includes 4 filters in the visible and 8 in the UV. The STIS visible FOV is 50 square arcsec and 25 square arcsec in the UV.

A comparison of the sensitivity of the WFPC2, STIS, ACS, and predicted WFC3 UVIS and IR channels is given in Figure 1. The throughputs include the OTA and instrument optics but do not incorporate filter transmissions. The ACS measurements have been made in ground-based testing and refer to the HRC, blue-sensitive SITe CCD detector.

2. To reflect the importance of the blue wavelength regime and the high blue sensitivity of the WFC3 UVIS channel, several blue filters - wide, medium and narrow band and a UV prism - are included in the UVIS filter set.
3. In contrast to WFPC2 and ACS, the WFC3 houses a large selection of narrow band filters. While the ACS filter compliment targets specific key programs, the WFC3 filter set contains a variety of filters which accommodate many astronomical topics.
4. WFC3 also contains several filters in common with WFPC2, NICMOS, and ACS to provide redundancy.
5. The latest technology of large format-high resolution CCD detectors will be incorporated into WFC3. The WFC3 CCD, a 2 2kx4k format, will have improved shielding and hopefully a smaller CTE degradation. Similarly, the HgCdTe detectors represent major advances over the predecessor NICMOS detectors, providing higher QE in the near-IR at passive (thermo-electric) cooling temperatures.
6. The narrow-band filter fabrication technology has improved since the WFPC2 manufacture era. The use of ion-assisted deposition processes improve the purity of the filter and guarantee a more sturdy filter with less likelihood for degradation of the coating.

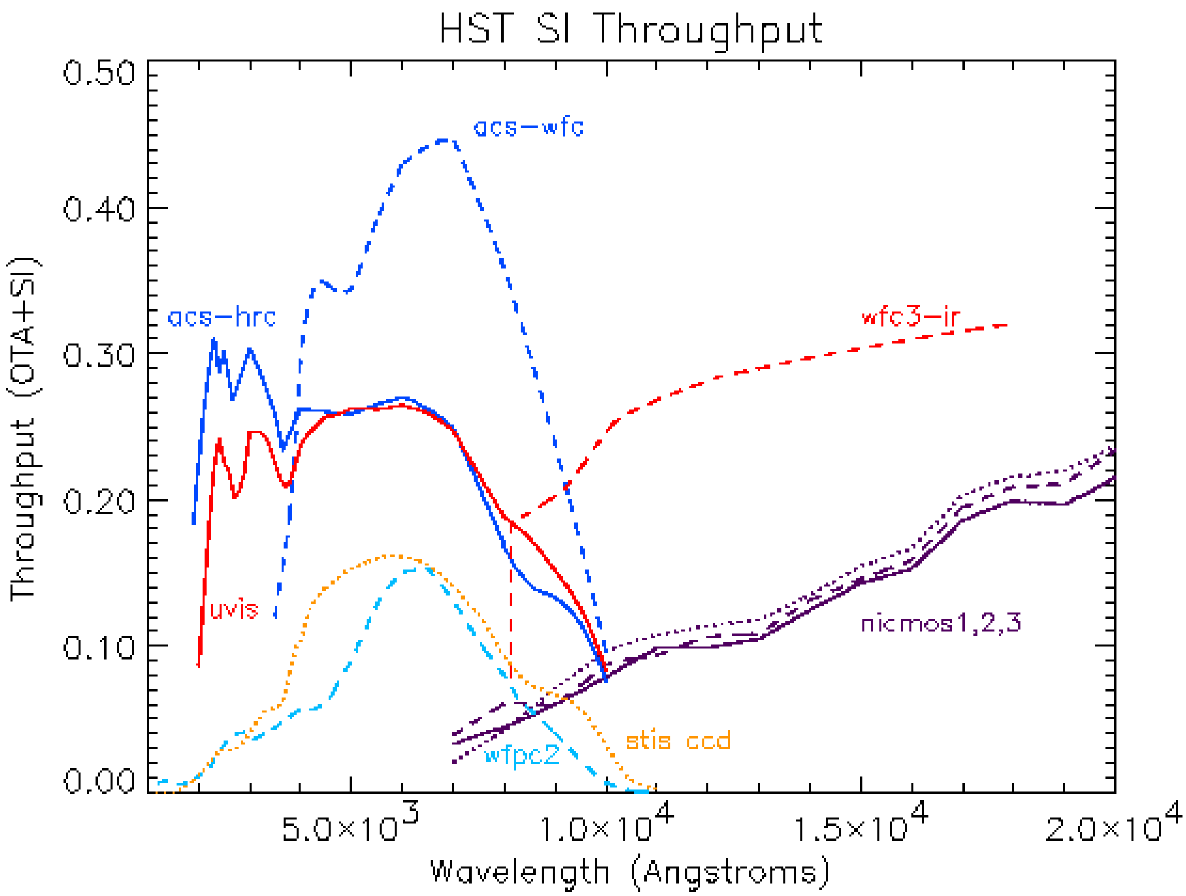


**Figure 1: HST Instrument Throughput Curves**. The WFC3 IR curve is from a Hawaii device, the WFC3 UVIS curve is a Lesser-coated SITe CCD. WFC3 values are approximate.

### *2.2 WFC3 IR Comparison to NICMOS*

The WFC3 near-IR channel design has a wavelength coverage from 8500A to ~1.7 microns. The detector, an HgCdTe focal plane array is an improved version of the NICMOS detectors, i.e., it will have ~ 4x higher sensitivity in the near-IR than the NICMOS NIC1 and NIC2 (plus the Cryocooler slated for insertion in 2001). The WFC3 IR channel FOV is larger: 135 x135 square arcsec compared to 50 and 19 square arcsec for NIC1 and NIC2 respectively.   The WFC3 IR channel will be cooled using a stacked thermoelectric cooler. The optical bench enclosure will be cooled to 0 degrees C, the filter wheel and cold optics to -40 degrees C, and the focal plane assembly will be cooled to ~120 degrees C. A series of heat pipes and an enhanced WFPC1 radiator will be used for thermal stabilization.

### *2.3 WFC3 UVIS and IR Optical Chains*

An optical block diagram for the WFC3 is shown in Figure 2.
The light from the OTA is intercepted by a fixed flat pick-off relay optic (POM) oriented at 47 degrees to the incoming beam which directs the beam to a flat mirror of the Channel Select Mechanism (CSM). The CSM either diverts the beam to the IR chain or, in its open position, allows the light to intercept the UVIS M1 mirror.

<u>The UVIS Channel</u>

As illustrated in Figure 3, the UVIS M1 hyperbolic mirror images the OTA pupil onto the M2 anamorphic asphere which performs the correction for the primary mirror spherical aberration. The M2 mirror re-images the light onto the CCD detector, first passing through the Selectable Optical Filter Assembly (SOFA) and then through two CCD enclosure windows. All the reflective surfaces in this channel have aluminum coatings.

Pertinent to the filter discussion is the SOFA, the re-furbished mechanism from the WFPC1. It contains 12 stacked filter wheels, each holding five 57-mm/side filters (see Figure 4). All filters must be parfocal so that there is a constant focus shift for all of the filters (equal to 5.5 mm of fused silica). The wavefront requirement through the filters comes from the overall budget in the CEI specification, i.e., over a diameter of 14mm, the transmitted wavefront error must < 0.02 waves at 6328A. The instantaneous footprint on the UVIS filter is between 10 and 14 mm for a filter in the front or in the rear of the SOFA assembly. The clear aperture is 53.238x53.238” square. Incident light is an F/31 with a light cone of incidence angle 0 to 3.13 degrees (SER-OPT-015, J. Turner-Valle,1999).

<u>The IR Channel</u>

The IR optical chain, shown also in Figure 3, is engaged when the CSM fold flat is positioned in the beam and directs the light to a fold flat and then to the IR M1 mirror. The M1 images the OTA pupil on the M2 anamorphic asphere. The M2 is an elliptic mirror with a tip/tilt mechanism. The light will intercept a etched cold mask which vignettes the secondary strut thermal image, then through a refractive corrector plate to the detector. The beam is corrected using a two-element system which reimages the pupil and a refractive corrector plate corrects for the spherical aberration. The filter select mechanism (IR FSM) comes after the refractive corrector plate and immediately in front of the IR detector housing aperture. All the mirrors in the IR channel are coated with silver to provide the highest reflectivity.

The IR filter wheel assembly is a single plate which houses 16 optical elements: 14 filters and two grisms, a blank, and a clear hole. The IR filter is a 25.4mm diameter circle of thickness equivalent to 4.0 mm+/-0.1 of fused silica. The angle of incidence of the F/11 beam is +/-4.6 degrees. The distance from the filter wheel to IR Focal Plane Assembly

(FPA) is ~123.488mm. The wavefront error is required to be 0.020 at 632nm over a throw of the 22 mm clear aperture.

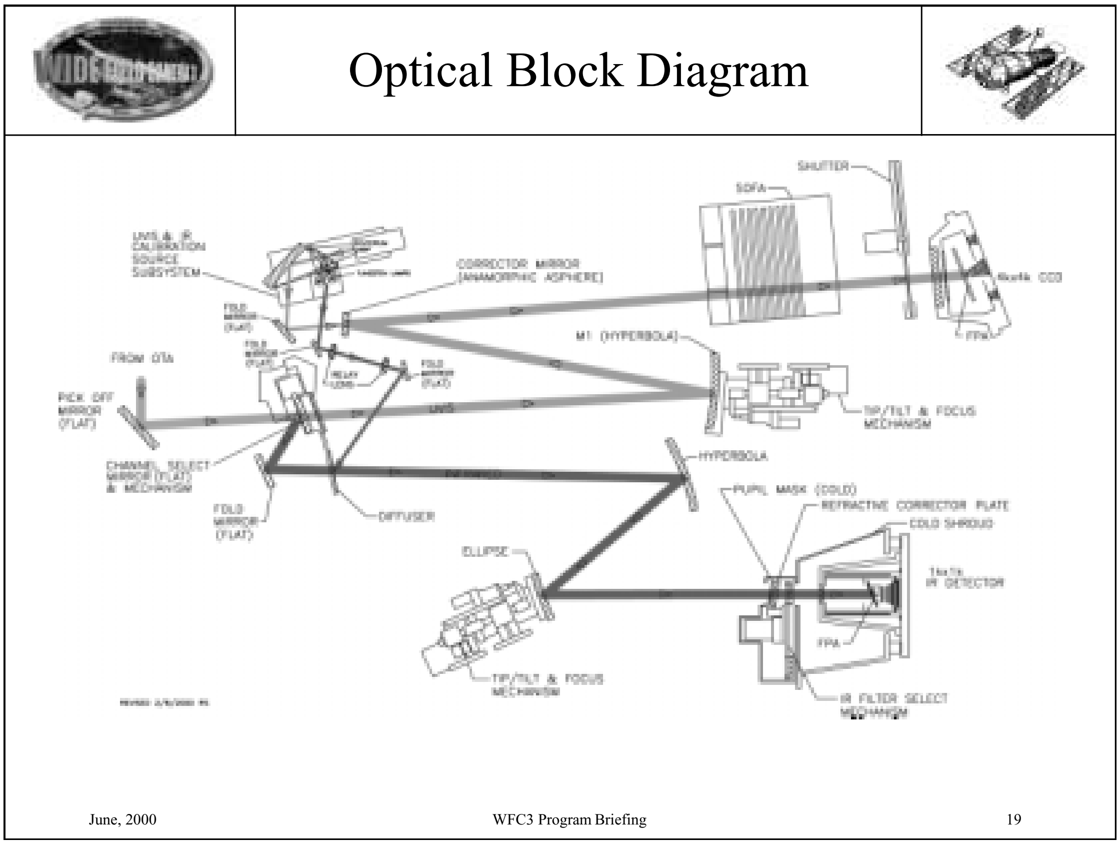


**Figure 2: WFC3 UVIS and IR Channel Block Diagram**.

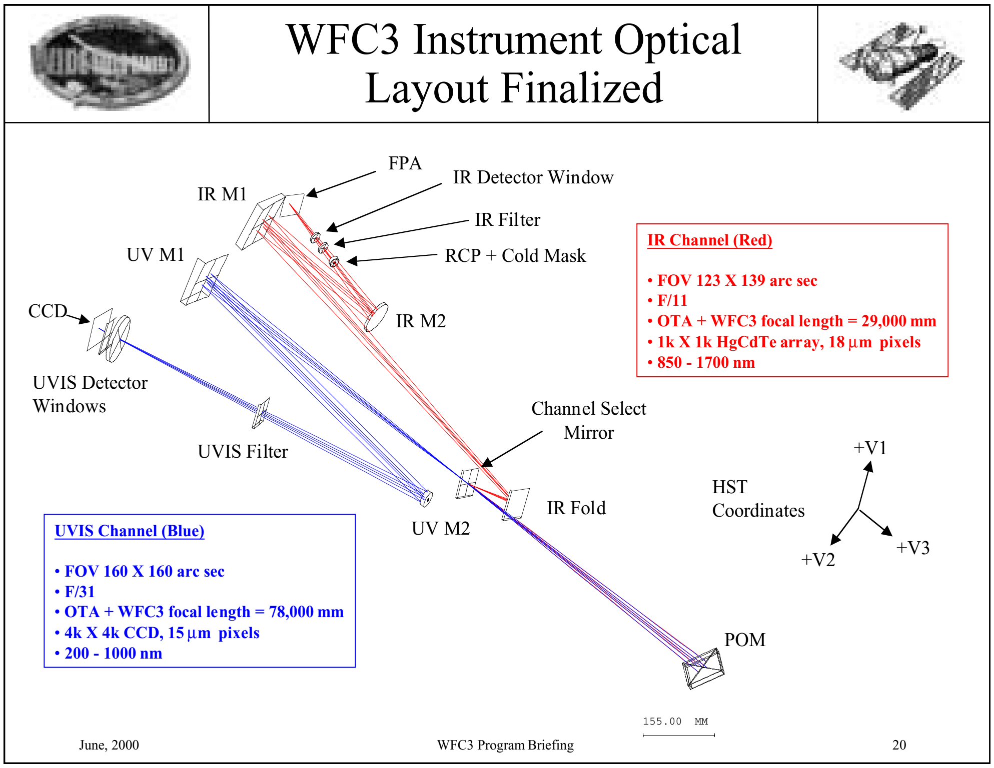


**Figure 3: WFC3 UVIS and IR Optical Design**.

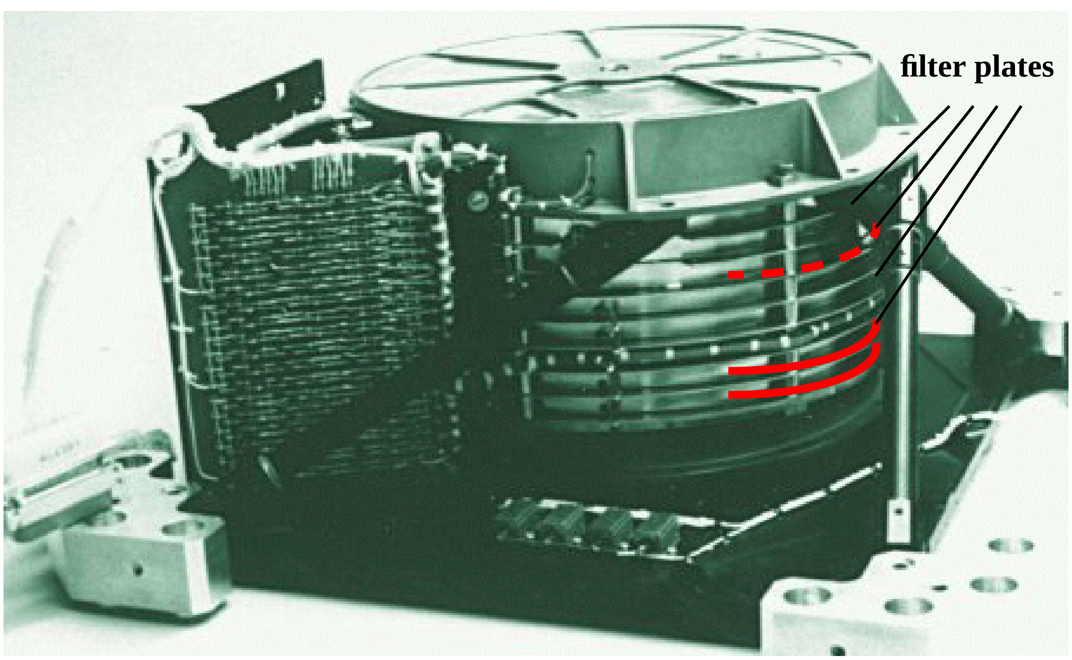


**Figure 4: WFPC1 Selectable Optical Filter Assembly (SOFA).**

## 3. HST Historical Filter Usage

To capture, in a general sense, the tenor of HST's historical filter prioritization and to identify trends which may provide additional insight into the needs of the community, a study was made of HST historical filter usage. The diagnostic statistics included the number of visits, orbits, total exposure time, the number of exposures, and the number of proposals (small, medium, and large categories). To get a sense of the importance of UV-blue sensitivity, filter statistics were tabulated according to Blue filters ($\lambda$ < 3000 and $\lambda$ < 4000A) and Red filters ($\lambda$ > 4000A). To look for trends in the narrow band versus broad or medium bands, filters were also grouped as narrow band (<50A fwhm), intermediate (50-300A fwhm) and broad (fwhm >=300A).

### *3.1 Description and Biases*

The study reported here includes data through the fall of 1998 and incorporates the following data base searches:

1. Proposal Management Data Base (PMDB) "ASSIST" data base with help from the PMDB for specific topics (courtesy Nancy Fulton and Steve Dignan,STScI).
2. Cycle 8 WFPC2 and STIS Imaging TAC Data Base (courtesy Brett Blacker, STScI).
3. HST Archive to spot check statistics.
4. WFPC2 Global Filter Summary (courtesy Sylvia Baggett, STScI) to verify consistency.

This survey focusses on specific questions relevant to filter selection and is not intended to be a robust statistical study. The following are known and understood biases and concerns:

- Complexities make it difficult to assess error bars.
- Prime exposures (GO/GTO/SNAPS) include GO-specified internal calibrations but the numbers are insignficant.
- Special Filters e.g., polarizers, ramps are not represented robustly.
- WFPC2 Dither Exposures are counted as single exposure.
- Multiple-Filter WFPC2 exposures were not addressed however the use of more than one filter was rare.
- Multiple-Filter FOC exposures are counted as the "narrow" filter in pair. This is adequate for general wavelength statistics.
- POS TARGS are each considered a single exposure. When POS TARGS are used to generate dithered exposures in WFPC2, the number of Wide Band observations are increased.

- Parallels: The numbers represent a 90% complete survey for WFPC2 only.
- Calibrations: for WFPC2, the attempt was made to eliminate FF frames and darks.
- Interpretation of “# Orbits”: the data base provides integer orbits only.

In Table 1, the completeness and integrity of the data used for this study are summarized.

**Table 1. Survey Completeness and Integrity**.

| SI IMAGER | MODES | PRIME (GO, GTO SNAPS) | Parallel | External Calib | SURVEY INTEGRITY |
|---|---|---|---|---|---|
| WFPC2 | Imaging | OK | OK | OK | good, Spot checks |
| WFPC1 | WFC+PC Imaging | OK | incom-plete | -- | unknown |
| FOC | FOC96+FOC48 | OK | difficult | no - multi-ple filters | Used only narrow filter of pair. |
| STIS | Imaging | OK | incom-plete | -- | some Target Acqui-sition (TA) contami-nation. |
| Cyc 8 WFPC2 | Imaging | No Snaps, includes parallel | -- | N/A | |
| Cyc 8 STIS | Imaging | No Snaps, includes parallel | -- | N/A | some TA contamina-tion; no snaps. |

### *3.2 Analysis and Results*

Several possible trends were addressed in this study such as the community need for blue sensitivity, propensity for narrow band programs vs. broad band, the wavelength and bandwidth regimes for the largest projects vs. small. Some of the trends occur due to lack of options, i.e., narrowband vs. broadband depend on narrowband filters available. *The authors recognize that this particular review lacks the robustness of folding in astronomical science priorities since it only deals with “numbers of exposures”. However, the general tendency for preferences of the community should be evident in this type of study*. A subset of results most relevant to WFC3 are summarized in this section.

***Top Ten Filters***

On the basis of past instrument design and usage, what are the top ten filters for WFPC2, WFCP1, and FOC***?*** *Table 2 lists the top ten filters on the basis of percent number of exposures for that instrument.*

**Table 2. Top Ten Filters based on the Percent Number of Exposures[1].**

| WFPC2[2] | %EXP | WFPC1[2] PC | %EXP | WFPC1 WFC | %EXP | FOC[3] | %EXP[4] |
|---|---|---|---|---|---|---|---|
| F814W | 27 | F336W | 34 | F555W | 24 | F220W | 30 |
| F555W | 17 | F555W | 18 | F785LP | 19 | F342W | 5 |
| F702W | 6 | F785LP | 8 | F702W | 16 | F430W | 5 |
| F850LP | 6 | F875M | 5 | F1042M | 11 | F152W | 5 |
| F675W | 5 | F502N | 4 | F875M | 6 | F486N | 4 |
| F606W | 5 | F889N | 4 | F656N | 3 | F480LP | 4 |
| F336W | 3 | F439W | 4 | F814W | 3 | F140W | 4 |
| F547M | 3 | F1042M | 3 | F502N | 2 | F175W | 3 |

**Note:** 1. Survey conducted 12/98 using PMDB "Assist" data base and PMDB (cour tesy N. Fulton and S. Dignan,STScI) archival checks (courtesy S. Baggett, STScI.
2. WFPC2 and WFPC1 multiple filter observations and special filter observations (ramps, polarizers) not included.
3. FOC multiple-filter observations are represented as the more narrowband of the pair.
4. Primes include GO/GTO/SNAPS.

***Increasing the Number of Filter Slots***

Do the statistics (not the science) suggest that previous instruments could have benefited from increasing the number of available filter slots, e.g., two SOFAs in the UVIS channel or more slots in the IR filter wheel?

No, a <u>significant</u> fraction of SI filters (using #exposures as the diagnostic) *each* contribute *less then 1%* of the total exposures, i.e., 80% of WFPC2 prime exposures were obtained in ~14 filters. *The number of filters per instrument for which the percent number of exposures is less than 1% is the following*:

WFPC2: 23 filters; PC-WFPC1: 18 filters;
WFC-WFPC1: 16 filters; FOC: 18 filters.

***The CCD to be Optimized in the Blue***

Do the statistics reveal an obvious demand for enhanced blue sensitivity and blue filters?

Yes, when the instrument is optimized for the blue regime (FOC), the modes are used extensively suggesting that an instrument optimized for the blue will be heavily subscribed. A summary is provided in Table 3. Figures 5 and 6 show the distribution of exposures (orbits and exposure time) as a function of blue ($\lambda$< 4000A), red ($\lambda$>4000) and very blue ($\lambda$<3000A) central wavelengths for WFPC2 and FOC, respectively.

**Table 3. Blue vs. Red Wavelength Regime**: Percent of total orbits, exposures, and proposals that used filters whose central wavelength is less than or equal to 4000A.

| SI | Blue $\lambda_c$<4000A %Orbits | Blue $\lambda_c$<4000A %Exp | Ratio Blue/Red Proposals | #Blue Filters/ Total filters |
|---|---|---|---|---|
| **FOC** | **78%** | **83%** | **3/1** | **34/45** |
| **WFPC1** | **8%** | **28%** | **1/6** | **12/66** |
| **WFPC2** | **14%** | **9%** | **1/5** | **13/44** |
| **STIS IMAGE** | **>28%** | **>23%** | **-** | **-** |

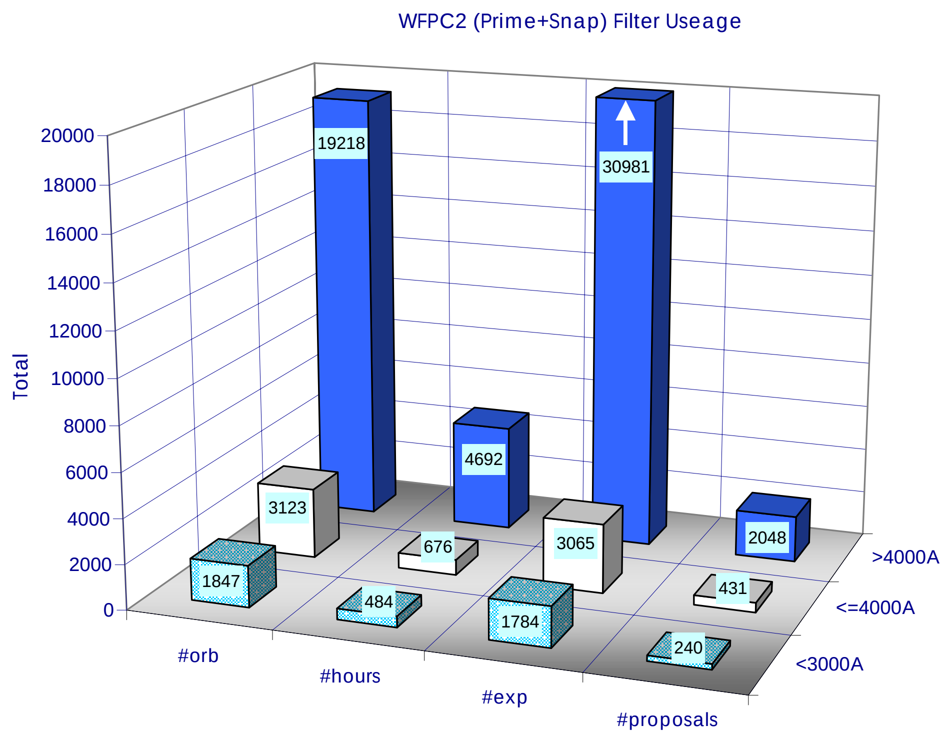


**Figure 5: WFPC2 Distribution**: Numbers of orbits, exposures, and hours as a function of wavelength grouping.

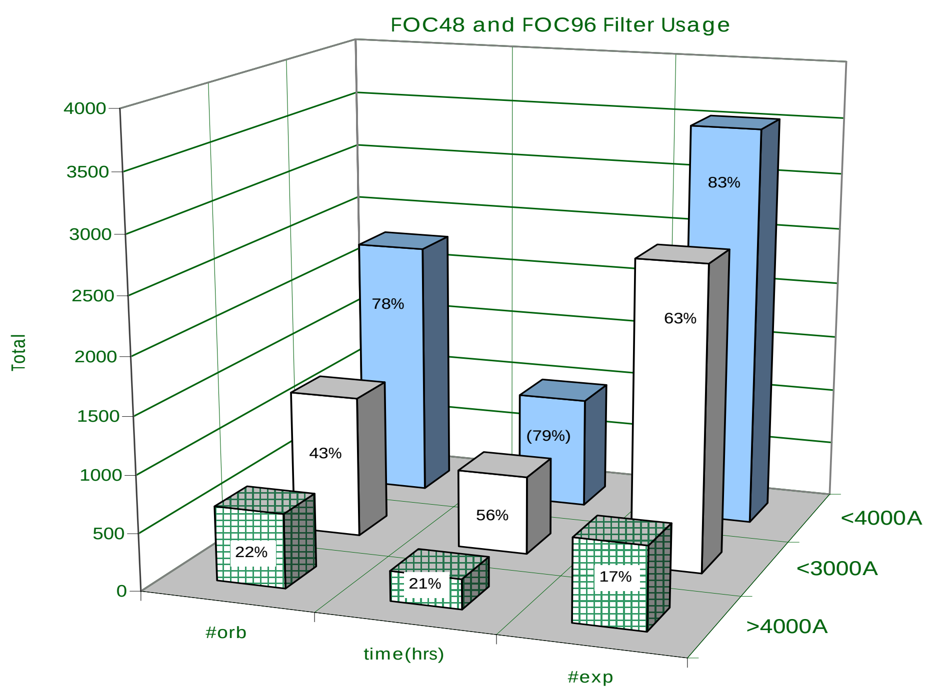


**Figure 6: FOC Distribution:** Numbers of orbits, exposures, and hours as a function of wavelength interval. Note the largest columns are associated with filters whose $\lambda_c$ is blue.

***Narrow vs. Broad Band***

Are narrow band filters used extensively and does a relationship exist between usage and filter bandwidth?

The data indicates that wide band filters (FWHM >300A) are preferred, however, individual narrow band filters do significantly contribute. The distribution of exposures according to width are shown in Table 4. Figures 7, 8, and 9 show the distribution of bandpass width as a function $\lambda_c$ for WFPC2, FOC, and WFPC1 respectively.

**Table 4. Filter Bandwidth:** Percentage of total exposures delineated by filter bandwidth: FWHM<50A, 50 < FWHM < 300A, and FWHM >300A.

| SI | FWHM>300A | FWHM<50A | 50<FWHM<300A |
|---|---|---|---|
| **WFPC2 Prime** | **85%** | **10%** | **<5%** |
| **WFPC2 Parallel** | **97%** | **-** | **-** |
| **FOC** | **78%** | **8%** | **15%** |
| **STIS** | **78%** | **-%** | **28%** |

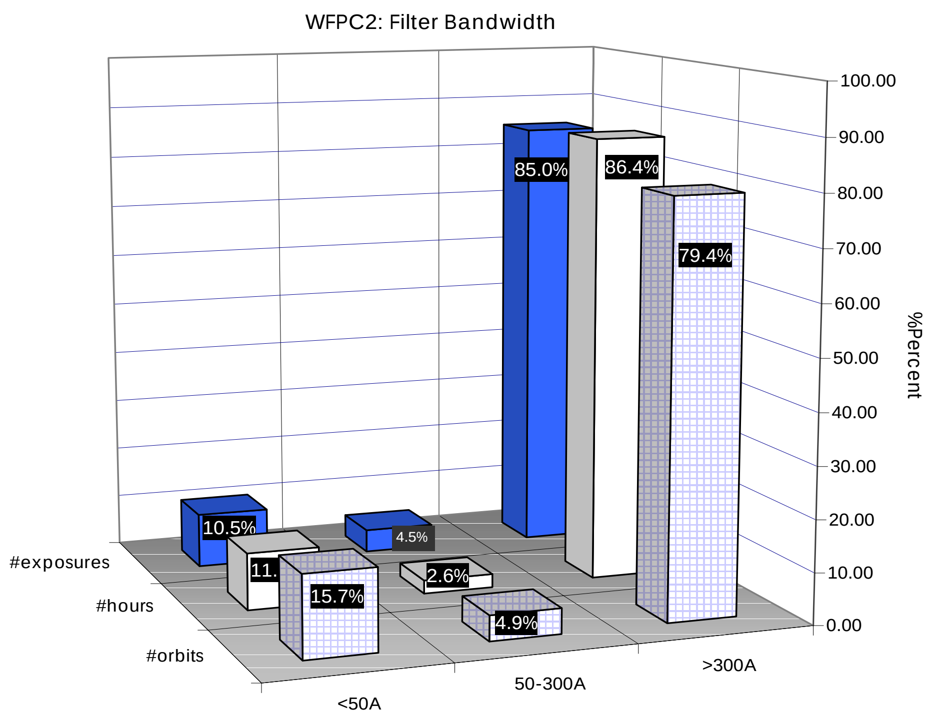


**Figure 7: Distribution of WFPC2 Orbits as a function of bandwith**.

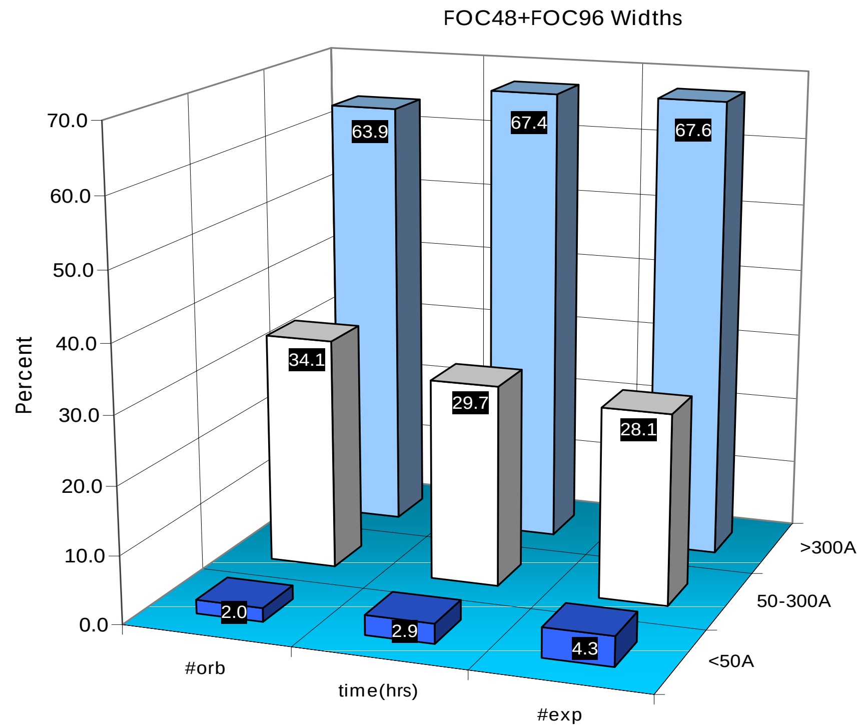


**Figure 8: Distribution of FOC orbits as a function of bandwidth**.

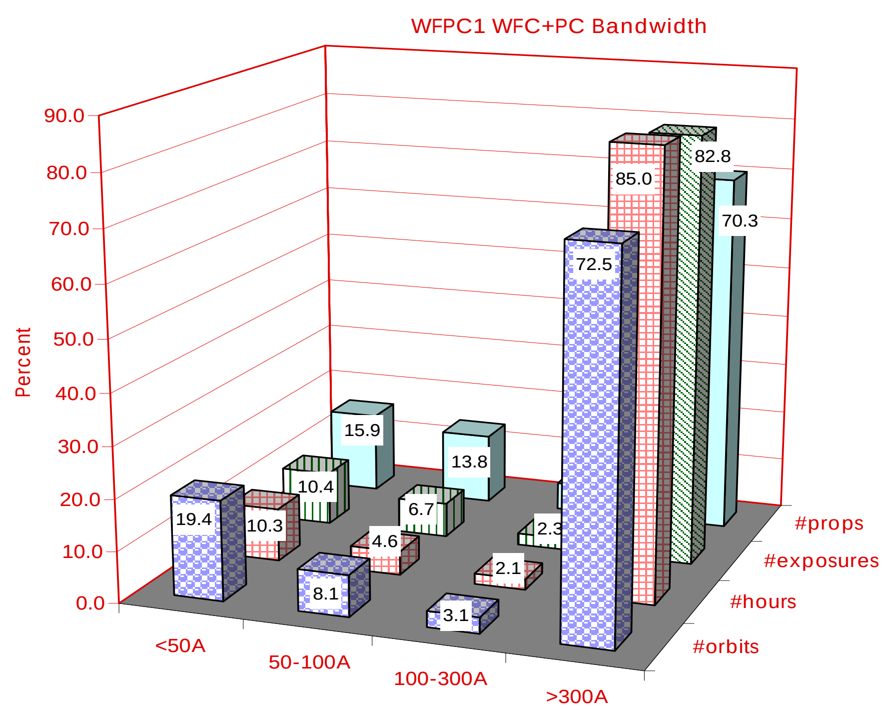


**Figure 9: Distribution of WFPC1 (WFC+PC) Orbits as a function of bandwidth**.

***Parallel vs. Prime, Red vs. Blue***

Is the distribution of the blue/red wavelength regimes different for parallel programs?

Yes, a significant increase of “blue”parallel observing is shown in Table 5 for WFPC2.

| Filter Central Wave | WFPC2 Prime+Snap Exposures | WFPC2 Parallel Exposures |
|---|---|---|
| **<=4000A** | **9%** | **29%** |
| **>4000A** | **91%** | **71%** |

**Table 5. WFPC2 Prime vs. Parallel Wavelength Regime**: Comparison of the central wavelengths for Prime (+Snap) and Parallel exposures.

***Large (Key) projects and propensity for wavelength regime***.
Does a trend exist between the number of blue observations and the size of the proposal i.e., small (<10 hours), medium (10-30 hours), and large (>30 hours)?

- WFPC2: Red Filters ($\lambda_c$>4000A) appear in 8x as many large proposals and 4x as many small proposals as blue filters.
- FOC (mostly small proposals).
- STIS: Blue filters appear in 1/3 as many small proposals and 2/3 as many large proposals as red filters.
- WFPC1: no information

The distribution with respect to proposal size is given for WFPC2 and STIS in Figures 10 and 11, respectively.

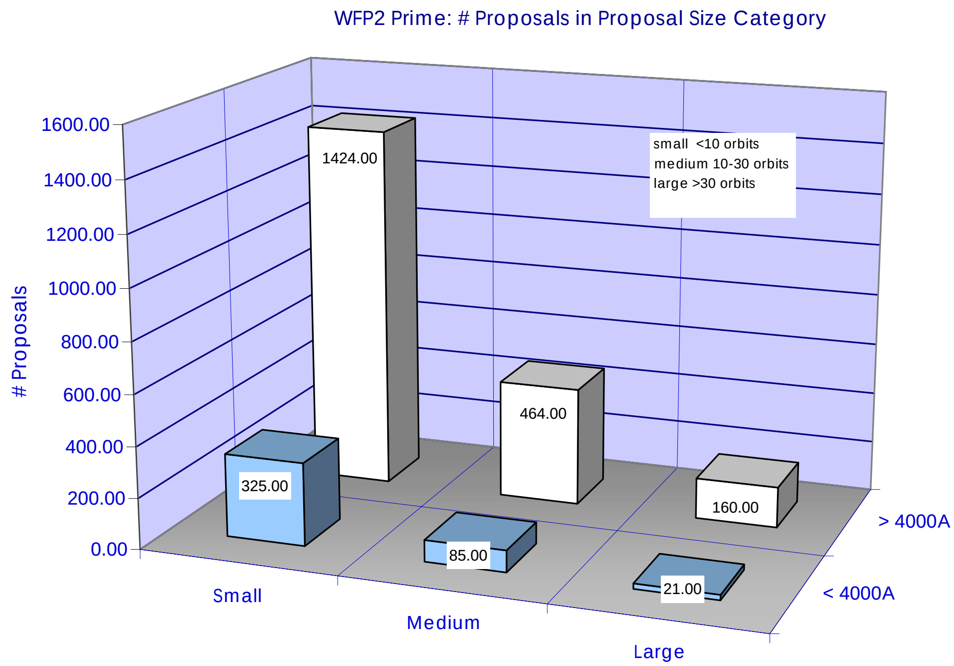


**Figure 10: WFPC2 Proposal Size**: Distribution of proposal sizes as a function of wavelength regime.

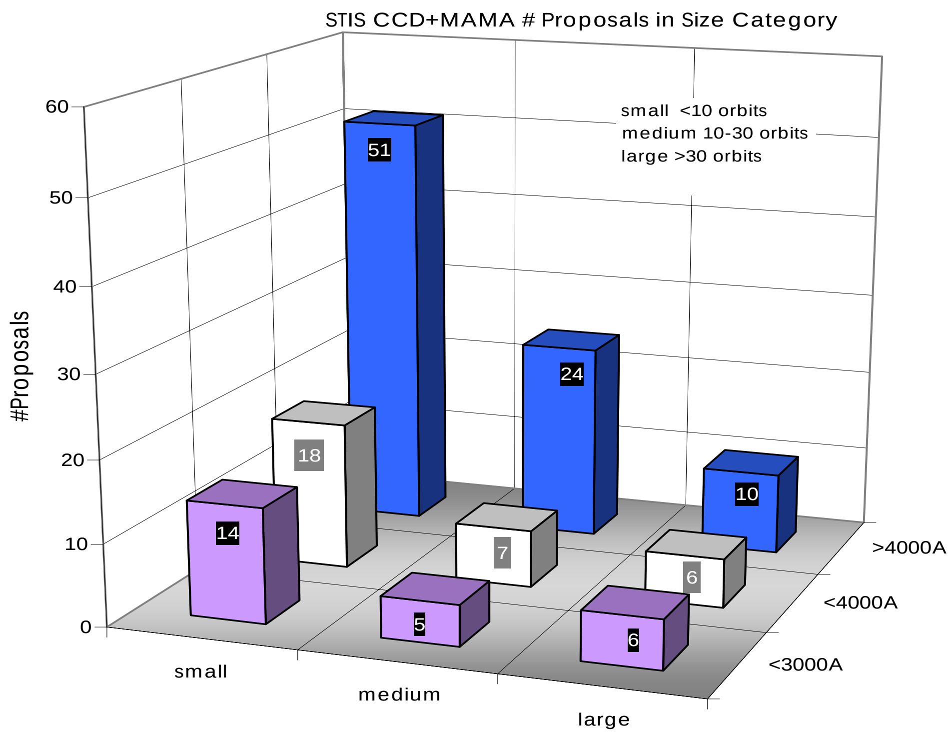


**Figure 11: STIS Proposal Size:** Distribution of proposal sizes as a function of wavelength regime

***What are the projections for ACS usage in the three wavelength regimes?***
Using the projections in the detailed Cycle 9 Reference Mission by *M Stiavelli (1997, ISR ACS-97-01)*. Massimo used a combined “prime+snap” data set from the archive (WFPC2, post SM1 FOC). The results are tabulated in Table 6.

**Table 6. An Early Prediction**: one prediction of the relative subscription of ACS cameras: SBC, WFC, and HRC in terms of percent exposures.

| | **<2000A** | **2000-3500A** | **>3500A** |
|---|---|---|---|
| StiavelliCombined | 2.8% | 10% | 87.2% |
| | **<3000A** | **<4000A** | **>4000A** |
| This Study | 11% | 19% | 70% |
| | **ACS SBC (<2000A)** | **ACS HRC (2000-4000A)** | **ACS WFC(>3500A)** |
| MS Proj. | 3% | 30% | 67% |

***How does the size of the pixel relate to the overall usage of the instrument in terms of wavelength regime?***
Using data for the WFCP2 (courtesy S. Baggett - archival search), the community usage of the PC was compared to that of the WFC. The WFC is used about 3x as much as the PC in terms of #orbits is shown in Figure 12. Figure 13 shows the distribution of PC and WFC orbits as a function of red ($\lambda_c$ > 3000A) and blue ($\lambda_c$ <3000A) filters.

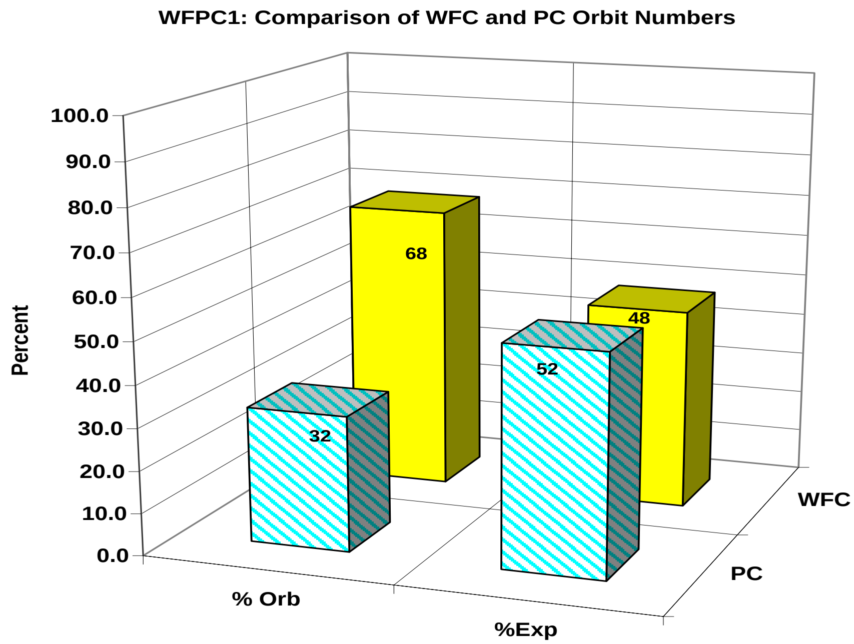


**Figure 12: WFPC2 Observational Modes**: Relationship between the number of PC versus the number of WFC orbits [archival data file through 2000 courtesy of S. Baggett].

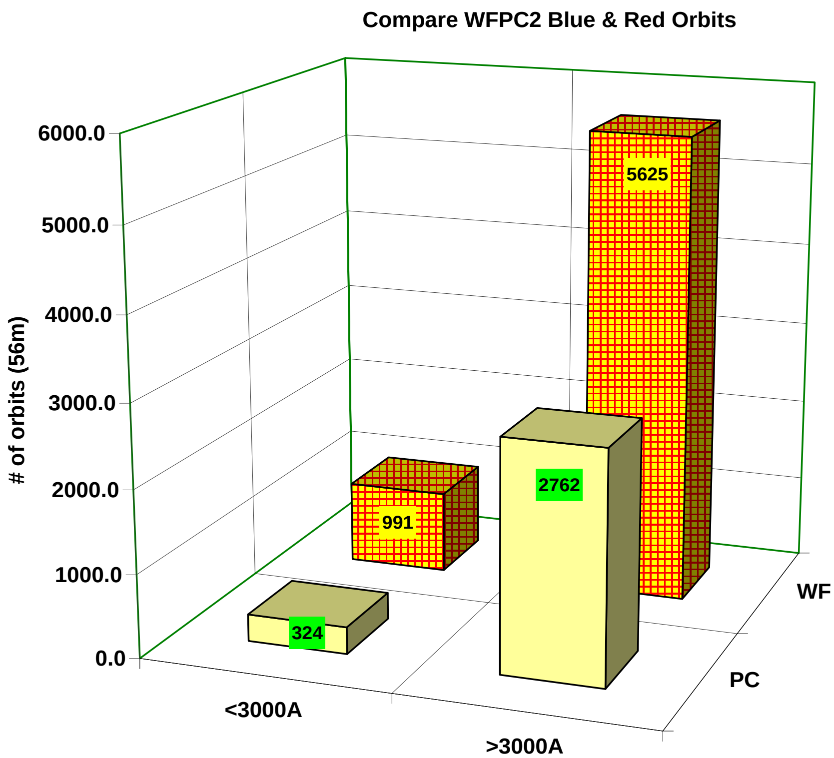


**Figure 13: WFPC2 Mode versus Wavelength Regime**: Distribution of the number of orbits obtained using red and blue filters as a function of WFPC2 mode (pixel size).

## 4. Summary

Adopting the premise that HST historical filter usage is one indicator of the filter needs of the astronomical community, we investigated the relationship between filter characteristics (central wavelength, FWHM) and the total number of orbits, exposures, programs. The results have been made available to the WFC3 Scientific Oversight Committee as part of the supporting material for their recommendation of a filter set for WFC3. General trends were assessed in a number of areas. The study was also designed to highlight unusual or special cases. We have shown that when an instrument is "blue-sensitive" it is used frequently by the community, suggesting that there are still many crucial programs which emphasize near UV wavelengths. Large parallel programs also emphasize near UV observations (although this could be due to a few very large programs). There is no supporting evidence that the community requires "additional" filter slots for WFC3 other than the SOFA for the UVIS and the single filter wheel for the IR channel, and in fact, only a handful of filters are used the greatest percentage of time. Narrowband filters are used less than Broadband as expected however their numbers are not negligible.

## Acknowledgements

For gracious help we thank S. Baggett, N. Fulton, and S. Dignan. For review and advice, we thank Pat Knezek, Massimo Stiavelli, and Pat Knezek.

### References

BALL SER OPT-015, 10-15-99 "WFC3 Optical Filter Requirements", J. Turner-Valle.

# APPENDIX

The following are some additional usage charts which may be of interest to the reader.

Combining the results for the HST Imagers, Figure A1 displays the distribution of observations as a function of wavelength interval. Figure A2 shows the relative contribution of calibration orbits from blue and red observations. Note that the ratio of blue/red calibrations is larger than the ratio of total WFPC2 blue/red observations.

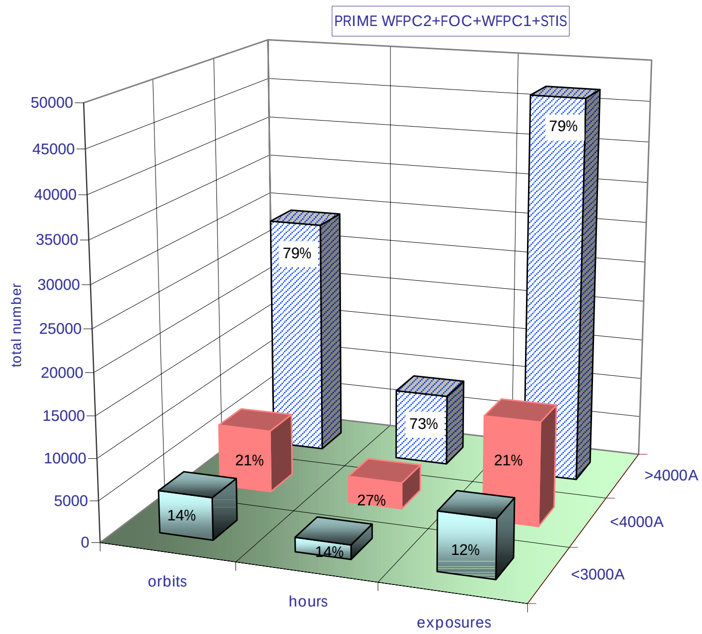


**Figure A1: Overall HST Imager Distribution:** #orbits as a function of wavelength interval.

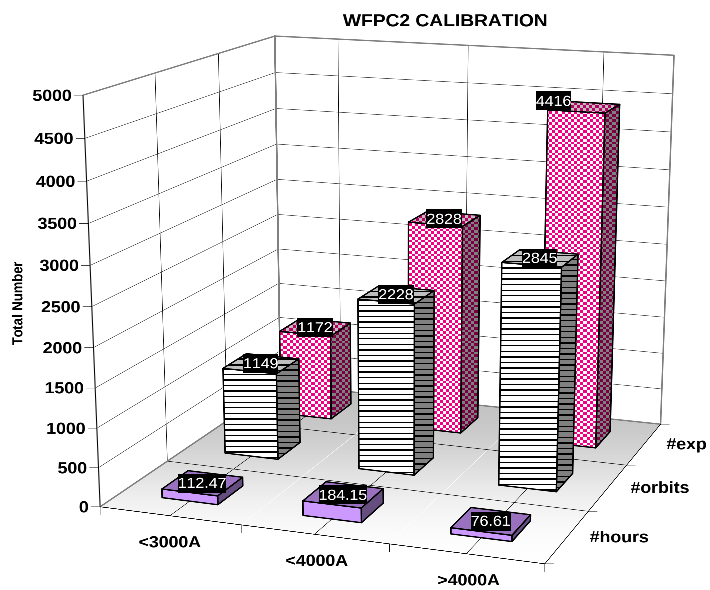


**Figure A2: WFPC2 Calibration:** #orbits as a function of wavelength interval.