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WFC3 Chip Dependent Photometry with the UV filters

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ABSTRACT

In this report we describe the expected countrates and computed inverse sensitivities in the UV for the two WFC3/UVIS CCDs, as implemented for the chip dependent photometric calibration. We describe how calwf3 applies the ratio of inverse sensitivity values for F200LP, F218W, F225W, and F275W to scale the UVIS2 counts to UVIS1, how different response functions naturally lead to these differences, and how the UV photometry keyword values for PHTRATIO and PHTFLAM1 are generated. Recommendations for obtaining accurate photometry are provided.

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1 Introduction

When the Wide Field Camera 3 (WFC3) was first placed in the Hubble Space Telescope during the 2009 Servicing Mission, the data reduction pipeline treated the array as a single detector with respect to photometric reduction. However, the two CCDs in the WFC3 instrument's UVIS channel come from different foundry runs and have different properties such as thickness and quantum efficiency, the latter of which is significantly different in the UV; and the chips age differently (cf. Gosmeyer & Baggett 2016). The desire to improve both the accuracy and the precision of WFC3 UVIS photometry led the WFC3 team to change how the WFC3 UVIS photometric calibration is determined: each CCD is treated independently. This "Two Chip Solution" calculates chip-dependent flatfields and photometry for each filter+CCD combination (Deustua et al 2016, Mack et al 2016).

One result of this change has been to expose the bandpass differences, i.e. the response functions, between the two detectors, particularly in the UV. The ratio of count rates between the two CCDs in a UV filter is about 2% higher than the ratio of the inverse sensitivities. This ISR describes the effect and provides recommendations for UV photometry.

2 Explaining the UV count-rate and response differences

Definition of the Mean Flux in a Bandpass

As defined in Bohlin et al. (2014), the photon weighted mean flux in a bandpass is calculated as:

$$\langle F \rangle = \frac{\int F_\lambda \, \lambda \, R \, d\lambda}{\int \lambda \, R \, d\lambda} \qquad \text{Equation 1}$$

where F_λ is the flux per unit wavelength (erg s^{-1} cm^{-2} $Å^{-1}$), R is the fractional throughput, i.e. total system efficiency as a function of wavelength, **λ**, and includes the detector quantum efficiency, as well as the reflectivity and transmissivity of all optical elements (mirrors, filters, dewar windows). The wavelength range over which integration is carried out have non-zero values of the throughput, R. The instrument count rate is N_e, in photoelectrons per second:

$$N_e = \frac{A}{hc} \int F_\lambda \lambda R d\lambda \qquad \text{Equation 2}$$

and the inverse sensitivity, S, is:

$$S = \frac{hc}{A \int \lambda \, R \, d\lambda} \qquad \text{Equation 3}$$

in units of erg s^{-1} cm^{-2} $Å^{-1}$ / e^{-} s^{-1} or as commonly found in HST documents, erg cm^{-2} $Å^{-1}$ / e^{-}, where A is the collecting area of the telescope, h is Planck's constant, c is the speed of light and R is the system response (fractional throughput). Thus,

$$\langle F \rangle = SN_e \; = \; photflam \times count\ rate \qquad \text{Equation 4}$$

Typically, the derivation of the photometric calibration is carried out using aperture photometry of standard stars, and hence, it is necessary to apply an aperture correction to the infinite aperture (where 100% of the star light is captured). Thus, in the HST nomenclature, photflam is the inverse sensitivity for an infinite aperture and is independent of the spectral energy distribution (SED) of the observed object.

Comparing Bandpasses: Mean Flux and Photflam

For one bandpass, the mean flux in the bandpass is F_1, its inverse sensitivity is S_1, and the measured count rate (e^{-}/s) is C_1. For a second bandpass, the values are F_2, S_2 and C_2, respectively. Thus the mean flux ratio is:

$$\frac{F_2}{F_1} = \frac{S_2 C_2}{S_1 C_1} \qquad \text{Equation 5}$$

and slightly rewriting it as :

$$\frac{F_2}{F_1} = \frac{S_2/S_1}{C_1/C_2} \quad \text{Equation 6}$$

Using the WFC3 nomenclature, where UVIS1 values are denoted by the subscript ‘1’ and UVIS2 values by the subscript ‘2’ for two similarly named bandpasses, the ratio of the mean flux in the two bandpasses is equal to S_2/S_1 (defined as PHTRATIO in calwf3) divided by the ratio of the instrumental count rates: N_{e1}/N_{e2} . In the trivial case where the mean flux in both bandpasses are identical, the inverse sensitivity ratio, S_2/S_1, is equal to the count rate ratio, C_1/C_2.

Figure 1 shows an example where the count rates in two different passbands are the same, but the mean fluxes differ. Bandpass B has twice the area as Bandpass A. The stellar flux in Bandpass A is twice that of Bandpass B and the mean flux ratio equals the PHOTFLAM ratio.

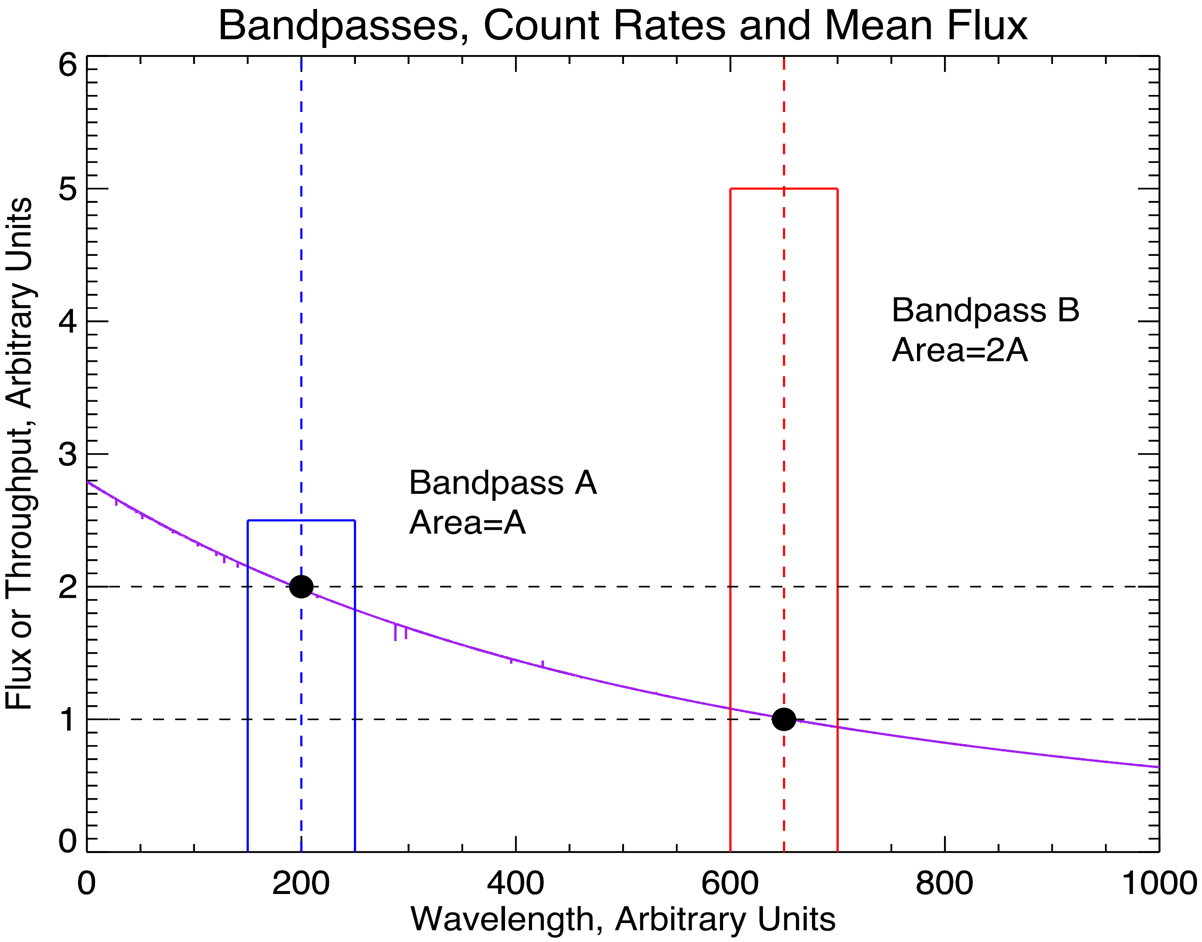

Figure 1. This cartoon is an example of two bandpasses wherein for a given spectral energy distribution the measured count rate is the same, but the mean flux (represented by the solid black circles) of each bandpass is different. Filled black circles represent the mean flux, where the purple line is a stellar SED.

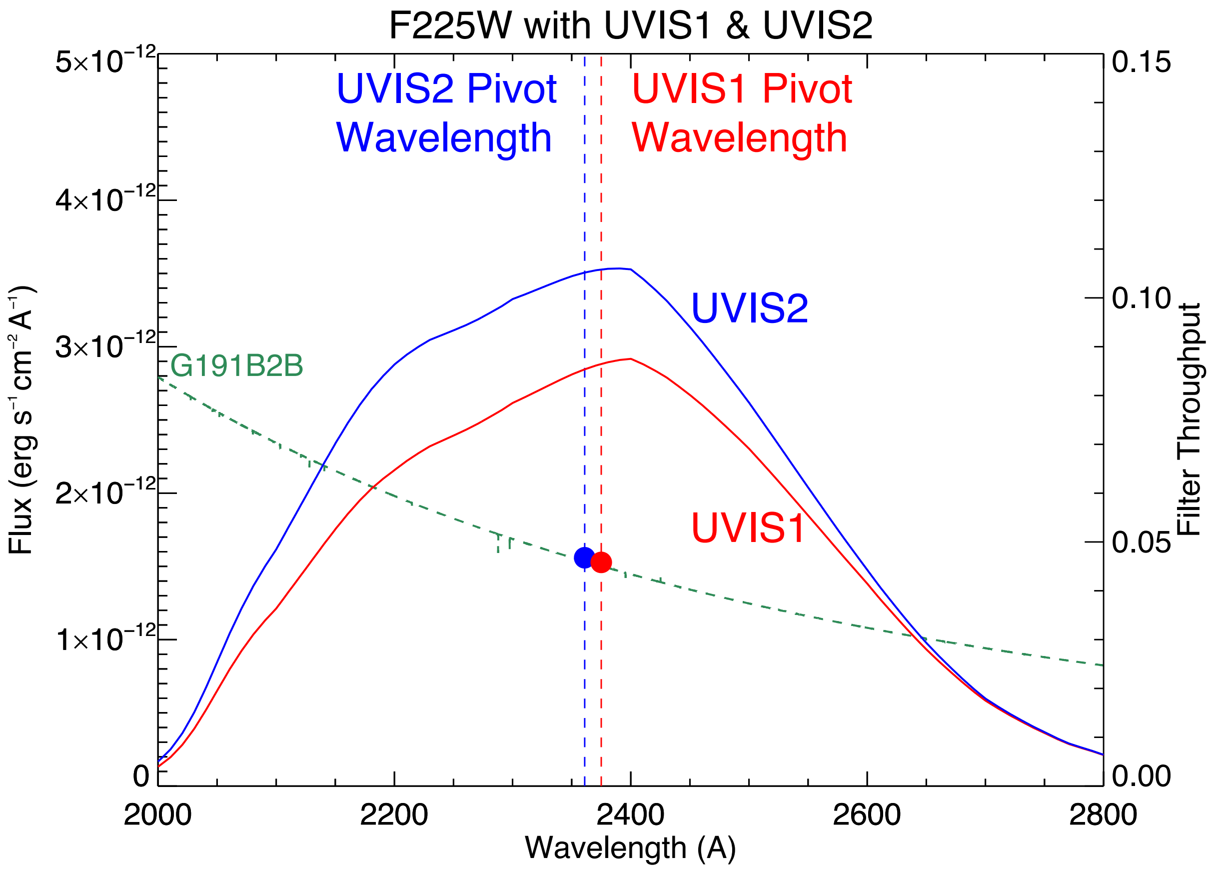

Figure 2. Plotted in blue is the UVIS2 F225W system throughput, where the blue vertical line marks its pivot wavelength at 2359 Å. The less sensitive UVIS1 F225W throughput is shown in red, and its pivot wavelength is marked with the red vertical line at 2379Å. The throughputs have been scaled to the flux of G191B2B, shown as the green dashed line. The mean fluxes, <f>, are marked with blue and red filled circles

Even when two systems (telescope + UVIS1 or UVIS2) use the same filter, the effective bandpasses can be dissimilar, as the response functions may be different, as shown in Figure 2. For the UV filters in the WFC3/UVIS channel the difference in the response functions, R, of the two detectors is greatest.

As an example, we compare the F225W filter plus UVIS1 and F225W plus UVIS2, for the three white dwarf standard stars, GD 71, GD 153 and G 191B2B. For the exposure times the statistical uncertainty is smallest at r = 10 pixels, hence we carry out the computations using count rates measured within a circular aperture of r = 10 pixels (0.3962"), which corresponds to an encircled energy fraction, EE, of 0.858 (Deustua et al. 2016, Appendix A). The mean flux, F, is thus calculated as F = S x (C/EE). Table 1 contains the infinite aperture inverse sensitivity values for UVIS1 and UVIS2, the measured count rates, the computed mean fluxes, and their ratios.

Variable	**G191B2B**	**GD153**	**GD71**	**Units**
UVIS1 Inverse Sensitivity, S_1		4.519E-18		erg cm^{-2} Å^{-1} e^{-1}
UVIS2 Inverse Sensitivity, S_2		3.751E-18		erg cm^{-2} Å^{-1} e^{-1}
UVIS1 Mean Flux, F_1=S_1xC_1/EE	1.5354E-12	3.1024E-13	3.7595E-13	erg s^{-1} cm^{-2} Å^{-1}
UVIS2 Mean Flux, F_2=S_2xC_2/EE	1.5740E-12	3.1760E-13	3.8400E-13	erg s^{-1} cm^{-2} Å^{-1}
UVIS1 Measured Count Rate at 10 pixels, C_1	291522.3	58906.2	71382.8	e s^{-1}
UVIS2 Measured Count Rate at 10 pixels, C_2	360010.1	72665.8	87856.8	e s^{-1}
Inverse Sensitivy Ratio, S_2/S_1		0.830		
Count Rate Ratio, C_1/C_2	0.810	0.811	0.812	
Mean Flux Ratio, F_2/F_1	1.025	1.024	1.022	
$(S_2/S_1)/(C_1/C_2)$	1.025	1.024	1.022	

Table 1. An example for the F225W filter, where aperture photometry on the two detectors shows that the ratio in the count rates is not equal to the ratio of the inverse sensitivities, because the response function of the detectors are different. This is shown graphically in Figure 2.

From Table 1 we see that the count rate ratio, C_1/C_2, and S_2/S_1, in the F225W filter are not equal, which is due to the different response functions of the UVIS1 and UVIS2 bandpasses. Results from all three stars are consistent within the uncertainty in the measurements, ~ 0.2%. See Section 4 for a discussion of count rate ratios for other stellar spectral types.

For reference, Table 2 provides the translation between the HST/WFC3 terms, the variables given in Equation 1 through Equation 6 and the UVIS image header keywords populated by the calwf3 pipeline. The subscripts identify the UVIS CCDs: 1 for UVIS1 and 2 for UVIS2.

Definition	**Symbol**	**UV**	**Header Keywords**
UVIS1 Inverse Sensitivity	S_1	S_1	PHOTFLAM
UVIS1 Inverse sensitivity	S_1	S_1'	PHTFLAM1
UVIS2 Inverse sensitivity	S_2	S_2	PHTFLAM2
Inverse Sensitivity Ratio:	S_2/S_1	S_2/S_1'	PHTRATIO
Count rate	N_e	N_e	
UVIS1 Count rate	C_1	C_1	
UVIS2 Count rate	C_2	C_2	
Mean Flux	<F>	<F>	
UVIS1 Mean Flux	F_1	F_1	
UVIS2 Mean Flux	F_2	F_2	

Table 2. Definition of the terms used, their equivalent variables, and keyword headers into which the corresponding variables are written by the WFC3/UVIS pipeline, calwf3.

3 Implementation of PHOTFLAM, PHTFLAM1, PHTFLAM2 and PHTRATIO in the WFC3 pipeline

Calibrated WFC3 data products (*flt.fits, *flc.fits) are combined to create distortion-free drizzled data products (*drz.fits, *drc.fits). AstroDrizzle assumes images are in units of counts or count rate and not in the flux units used for photometry, which means that the same (hot WD) star must have the same count rate on both chips to make the drizzle software work. This section explains the consequences of multiplying the UVIS2 count rates by C_1/C_2 to satisfy the drizzle requirement. When the responses are different, the process of drizzling together images from different UVIS filters, detectors and/or different instruments is complicated, e.g. WFC3/UVIS1 with WFC3/UVIS2 or WFC3/UVIS and ACS, or WFC3/UVIS and WFPC2. As we showed in the previous section, when the response of two system throughputs is different, the inverse sensitvity values will not be the same (and neither will the mean fluxes).

In the WFC3/UVIS image headers, the inverse senstivity information is written into keywords PHOTFLAM, PHTFLAM1, PHTFLAM2, and, the ratio PHTFLAM2/PHTFLAM1 defines PHTRATIO. Keywords ending in '1' are for chip 1, and those in '2', are for chip 2 . In contrast, the ACS/WFC provides one value for the inverse sensitivity that is written to the header keyword PHOTFLAM. WFC3/UVIS keeps the PHOTFLAM keyword, where the S_1 values for chip 1 are always written (see Deustua et al 2016 for further explanation). Because the response of the two WFC3/UVIS detectors is significantly different in the UV, WFC3 now provides a value for PHTFLAM1 = S_1' for four UV bandpasses: F200LP, F218W, F225W and F275W, instead of the actual S_1 used for the bulk of the filters. This term S_1' is defined so that PHTRATIO=PHTFLAM2/PHTFLAM1 matches the count rates ratio of the two chips, i.e.

$$S_2/S_1' = C_1/C_2 \qquad \text{Equation 7}$$

or

$$S_1' = S_2 \; C_2/C_1 \qquad \text{Equation 8}$$

For more discussion regarding instrumental count rates for UV filters, see Mack (2016).

The IMPHTTAB photometry look-up table is used by calwf3 to populate the image header keywords, which are then used to scale the UVIS2 science array by the C_1/C_2 ratio to match the count rates in UVIS1. For ALL full-frame filters, the correct sensitivity value for UVIS2 is written into the PHTFLAM2 keyword, the correct sensitivity value for UVIS1 is written into the PHOTFLAM keyword, and, for all *BUT the four UV filters*, the correct sensitivity value for UVIS1 is also written into the PHTFLAM1 keyword. For F200LP, F218W, F225W and F275W, the PHTFLAM1 value is tweaked so that PHTRATIO for these filters is equal to the count rate ratio. Table 3 lists S_1' and the $S_2\,/S_1'$ values for the four UV filters. All values of S_1', S_2 and S are for the infinite aperture ~~inverse~~. Count rates are measured for a circular aperture with r=10 pixel radius and corrected to the infinite aperture. The calculated values are then as shown in Table 3.

Item	**Header Keyword**	**F200LP**	**F218W**	**F225W**	**F275W**
UVIS1 Pivot Wavelength	PHOTPLAM	4989.2	2228.8	2373.3	2710.4
UVIS2 Pivot Wavelength	PHOTPLAM	4889.2	2224.4	2359.5	2704.0
Count rate ratio, C_1/C_2	n/a	0.9342	0.7738	0.8110	0.9428
UVIS1 Inverse Sensitivity,	PHOTFLAM	4.66567E-20	1.44562E-17	4.51883E-18	3.18585E-18
UVIS2 inverse sensitivity (S_2)	PHTFLAM2	4.75278E-20	1.12973E-17	3.75053E-18	3.04219E-18
Inverse sensitivty ratio (S_2/S_1)	n/a	1.0187	0.7815	0.8300	0.9549
UVIS1 Inverse Sensitivity (S_1')	*PHTFLAM1*	*5.0879E-20*	*1.4600E-17*	*4.6248E-18*	*3.2268E-18*
Inverse sensitivity ratio: (S_2/S_1')	*PHTRATIO*	*0.9341*	*0.7738*	*0.8110*	*0.9428*

Table 3. UV values of the true and tweaked (in italics) inverse sensitivities, and the header keywords into which they are written. Italicized entries are for S_1', which is equal to S_2 x C_2/C_1-

4 Calculating the Mean Flux

CALWF3 computes PHTRATIO by dividing PHTFLAM1 into PHTFLAM2: (PHTRATIO = PHTFLAM2/PHTFLAM1), and then scales the UVIS2 science image to match the UVIS1 count rate, C_1, by multiplying the UVIS2 count rate, C_2, by PHTRATIO. (i.e. C_2 x PHTRATIO). One calculates the mean flux (in ergs/s/cm^2/Å) by multiplying the calwf3 processed image by PHOTFLAM, namely

$$<F_{uvis1}> = C_1 \times \text{PHOTFLAM}$$

$$<F_{uvis2}> = [C_2 \times \text{PHTRATIO}] \times \text{PHOTFLAM} = C_2' \times \text{PHOTFLAM}$$

Where C_2' is the pipeline produced image counts, i.e. $C_2' = C_2 \times PHTRATIO$.

BUT, for the four UV filters, the mean flux in Chip 2, $<F_{uvis2}>$, is calculated thus:

$$<F_{uvis2}> = C_2' \times PHTFLAM1$$

Users are reminded that for aperture or point-spread function photometry of point sources the appropriate aperture correction should also be applied.

Alternatively the same result is achieved by reprocessing the raw data with calwf3, setting the FLUXCORR switch to OMIT. Then, the flux in each detector is calculated by multiplying UVIS1 x PHOTFLAM and UVIS2 x PHTFLAM2 (cf Ryan et al 2016 and Bajaj 2016).

5 Photometry with the UV Filters

UV photometry may be computed directly from calibrated data products (*flt.fits or *flc.fits) corrected for distortion using the UVIS pixel-area map. Alternately, for photometry on drizzled data products, users are advised to drizzle each chip (in units of counts) separately prior to performing photometry. This makes it easier to keep track of which inverse sensitivity value to use with which output pixels and is especially important when combining observations obtained at different orientations or with large (eg. chip gap) dithers. The following two lines demonstrate how to drizzle the two UVIS chips separately (in python):

```
>>> astrodrizzle.AstroDrizzle(‘*flt.fits’, output= ‘UVIS1’, group= ‘sci,2’)
```

```
>>> astrodrizzle.AstroDrizzle(‘*flt.fits’, output= ‘UVIS2’, group= ‘sci,1’)
```

Confusingly, the UVIS2 image is written into the 1st extension of the flt.fits file, and is the first science images, hence ‘sci,1’, whereas the UVIS1 image is written iinto the 4th extension but is the second science image, thus ‘sci,2’ (cf the WFC3 Data Handbook).

This is the correct way to proceed, as otherwise the sources on the two chips will not be properly flux normalized.

Ultraviolet UVIS1 and UVIS2 count ratios for hot and cool stars

The only purpose of the tweaked value, S_1’ is to match the UVIS1 and UVIS2 count rates to make Astrodrizzle work when observing with the four UV filters, F200LP, F218E, F225W, and F275W. But, the drizzle products made this way do not preserve precise photometry for stars cooler than T ~ 20 000K, which, will have different count rate ratios. Figure 3 illustrates this important point. In the UV, an AV star’s SED (T ~ 10 000 K) is almost flat and $C_2 \sim C_1$, whereas the SED of white dwarf G191B2B (T ~ 30 000 K), is decreasing with wavelength and $C_2 > C_1$, while the cooler GV’s SED (P330E, T ~ 5 000 K) increases with wavelength and $C_1 \geq C_2$ This issue will be studied and presented in a forthcoming ISR.

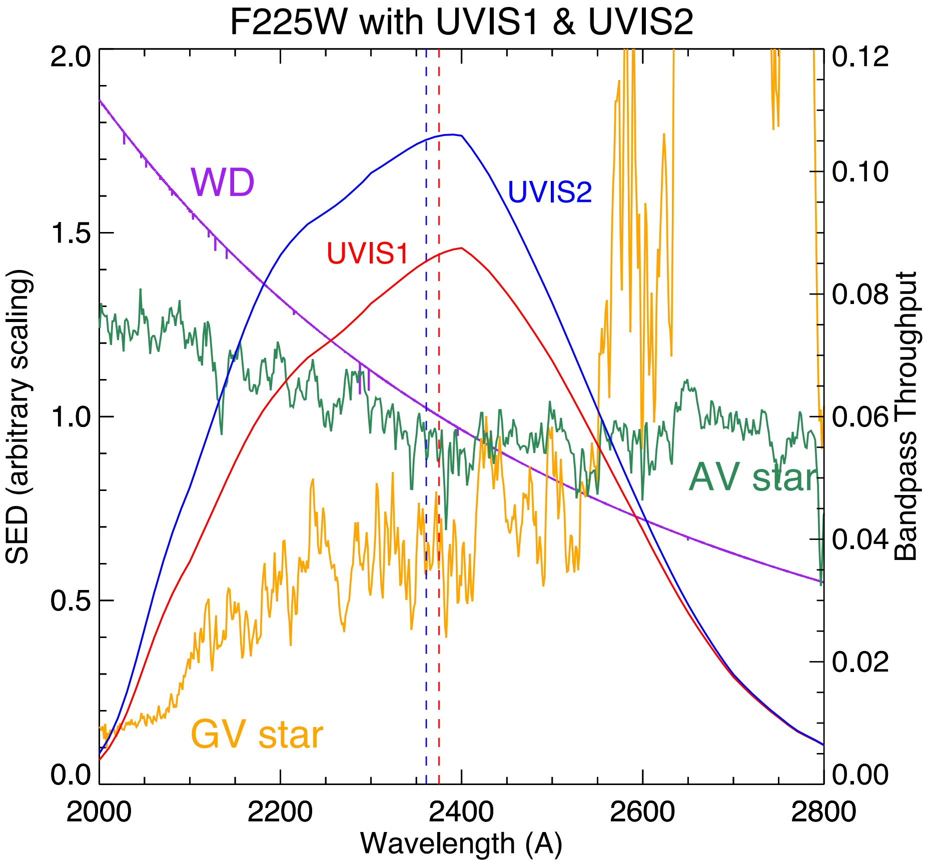

Figure 3. As in Figure 2, with the addition of the spectral energy distributions of a GV star (yellowish solid line) and for an AV star (green solid line). The WD SED is shown in purple. An arbitrary scaling is applied to each SED to normalize them to ~1 at 2400 A. An A star will have almost flat SED in the UV, whereas that of a cooler star will decrease towards the shorter wavelengths. Thus their count rate ratios (C_1/C_2) will differ from that of the much hotter WD G 191B2B

6 Conclusions

The two WFC3/UVIS detectors have different properties, with the largest differences manifested in the UV; thus, the instrumental count rate ratios of the two CCDs, (C_1/C_2) will not be the same as the ratio of inverse senstivities (S_2/S_1).

Because AstroDrizzle operates in count rates and not in flux units, we provide values of S_1' for the UV filters (F200LP, F218W, F225W and F275W), such that the PHTRATIO values in the image headers match the observed count rate ratios for hot white dwarf standard stars, i.e. $S_2/S_1' = C_1/C_2$. Redder/cooler stars with the UV filters are likely to have different count ratios. Color effects will be treated in a future report.

7 Recommendations

For many applications, the difference for the two detectors (up to 2%) is small compared to the photometric errors, so using a single PHOTFLAM value is reasonable. For accurate UV photometry we recommend calculating the mean flux in each detctor as in section 4. UVIS1 images will always have the correct flux simply by multiplying by PHOTFLAM. The UVIS2 UV images should be multiplied by PHTFLAM2, if treated separately and when reprocessed with FLUXCORR = OMIT in calwf3.

8 Acknowledgements

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9 References

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NOTES

WFC3 UVIS Photometry Lookup Table: The WFC3/UVIS photomety lookup table, IMPHTTAB, called by calwf3, contains the inverse sensitivity values, pivot wavelength and bandwidth for each filter and CCD combination. The structure of the IMPHTTAB is described in Deustua et al (2016). The list of current and past reference files are available from CRDS (Calibration Reference Data System) at https://hst-crds.stsci.edu/ .