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# Calibration of the WFC3-IR Count-rate Non-linearity, Sub-percent Accuracy for a Factor of a Million in Flux

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## ABSTRACT

*Previous analyses have shown that WFC3-IR suffers a count-rate dependent non-linearity of about 1% per dex, an order of magnitude smaller than the prior HgCdTe detector, NICMOS, flown on HST, but large enough to potentially limit the accuracy of photometry. We present new and more precise measurements of count-rate non-linearity (CRNL) through a combination of comparisons of cluster star photometry between WFC3-IR and WFC3-UVIS and by using observed and synthetic magnitudes of white dwarfs. We further extend the measured range of CRNL to higher count rates by comparing magnitudes between the ground and WFC3-IR for LMC and Milky Way Cepheids. Combining these results with all previous measurements and those from the WFC3 grism provides a consistent and improved characterization of the CRNL of WFC3-IR, of 0.75% +/- 0.06% per dex, with no apparent wavelength dependence, measured across 16 astronomical magnitudes. To illustrate the value of the precision reached for the CRNL, we show it is sufficient to compare the photometry of sources along a distance ladder calibrated by Gaia parallaxes and produce a 1% determination of the Hubble constant.*

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## Introduction

Parallax measurements from the ESA Gaia mission are being used to calibrate the absolute fluxes of stellar class objects to percent level precision. However, with this new leverage comes the need for greater reliance on accuracy along the scale of *apparent* or brightness measurements.

Comparisons between fluxes of Milky Way stars and their extragalactic cousins require a flux scale which is accurate across tens of astronomical magnitudes or factors of millions in flux.

Space observatories can uniquely collect the necessary photon statistics for such comparisons due

to their low background and stability. However, such comparisons rely on the linearity of flux (or magnitude) measurements across this large dynamic range. Establishing the accuracy of the flux scale is challenging in the NIR because HgCdTe infrared detectors suffer *count-rate* non-linearity (CRNL; also known as failure of reciprocity or the “Bohlin Effect”; Bohlin, Linder, Riess 2005) which is detector-specific and difficult to measure. The mechanism of this type of non-linearity is not fully understood but it appears to result from charge trapping which also produces the phenomenon of image persistence (Smith et al. 2007). Image persistence is regularly seen on the NIR detectors on HST after exposure to a bright source (though rarely seen from the ground due to higher backgrounds which mask the persistent image.) CRNL should not be confused with the well-known *total count* non-linearity which occurs as charge collection approaches full-well depth and which is more easily characterized (and corrected) by varying the integration time of a standard source, in the lab or on-orbit (Hilbert 2008).

For the first generation of NIR detectors on HST, NICMOS, CRNL was substantial, ranging from 3% to 10% loss in measured flux per factor of ten decrease in flux depending on the detector and wavelength. Because flux zeropoints are established from standard stars which are about ten astronomical magnitudes (4 dex) brighter than faint, sky-dominated targets, the impact on photometry of faint objects would reach a few tenths of a magnitude. With NICMOS, it was possible to measure the CRNL directly using the on-instrument lamp, which could be turned on during observations. The lamp artificially increases the count-rate of sources by a known amount (measured from regions of blank sky), and the difference between the measured count rate for sources with and without the lamp was used to quantify the effect. The CRNL of WFC3-IR was expected to be an order of magnitude smaller than NICMOS based on lab experiments with similar detectors to that used for WFC3. However, while WFC3 also includes a calibration lamp, it cannot be used during on-sky exposures, making it challenging to directly measure the CRNL. Even a more modest 1% per dex CRNL can rise to a net effect of  $\sim 0.06$  mag when comparing Milky Way stars at 1 kpc ( $m-M=10$  mag) to extragalactic equivalents at 1 Mpc ( $m-M=25$  mag) challenging the accuracy of WFC3-IR photometry if not well characterized.

Due to the difficulty of measuring CRNL for WFC3-IR on orbit, a broad set of approaches have been used. The initial, on-orbit calibration of CRNL (see Table 1) was produced by Riess (2010) who compared the magnitudes of stars in clusters between two overlapping passbands, one from an instrument without CRNL (the CCDs of ACS WFC) or corrected for CRNL (NICMOS) and WFC3-IR. An alternative approach was used by Riess and Petro (2011) who tried to mimic the augmented background approach available with the NICMOS lamp by observing cluster stars with nominal background and with elevated background reached during close approach by HST to the bright Earth limb. However, the angle of approach to the Earth is limited to above 10 degrees to allow the FGS to operate and retain sharp images (otherwise the bright Earth would swamp the FGS causing loss of lock). Thus the level of background remains modest (limited to a few  $e/sec$ ). Because the percentage increase in count-rate for stars with this level of limb light is small, the

statistical precision of these measurements was much less than possible with a lamp.<sup>1</sup>

A third approach used by Riess (2011) compared the measured fluxes of bright stars in asterisms observed by 2MASS and WFC3-IR in overlapping bands. As shown in Figure 1, these measurements consistently demonstrated that the WFC3-IR CRNL was small, 0.011 +/- 0.0031 mag/dex measured across 4 magnitudes from Riess (2011) was a good summary of all of the measurements. However, the uncertainty multiplied by an application of the correction across 6 dex (15 astronomical magnitudes) produced a non-trivial net ~0.02 mag uncertainty (indeed a dominant error for a future, 1% determination of the Hubble constant via a distance ladder calibrated by Gaia and built from standard candles). An improvement by a factor of 2-3 and established over a wider dynamical range is highly desirable.

Here we present additional sets of measurements which provide greater precision in the on-orbit determination of the WFC3-IR CRNL. First we present new measurements comparing cluster star magnitudes in bands where CCD's overlap with WFC3-IR, F850LP, and F098M using a combination of deep and shallow frames to extend the dynamic range. We also provide calibrations of the CRNL at brighter magnitudes (F160W=6-14) using comparisons between the ground and WFC3-IR of the photometry of Cepheids in the Large Magellanic Cloud and the Milky Way. Then we use an independent approach. We compare the near-infrared photometry of hot, DA White Dwarf (WD) to models constrained by optical measurements.

### **Stars in 47 Tuc: WFC3-UVIS (F850LP) vs WFC3-IR (F098M),**

Program GO 14868 obtained observations of stars in May and June 2017 in a field offset 6' West from the core of 47 Tuc (ra=00:21:22.2, dec=-72:02:39). This field was selected to reduce crowding which could complicate the photometric comparison of the stars observed at different resolution (primarily a result of the different pixel size of WFC3-IR and WFC3-UVIS) and focus. The WFC3-IR observations were obtained over a full orbit in F098M (visit 4) using a dither box to cover the larger area of the WFC3-UVIS detector (4x400 sec, sampseq=STEP100, NSAMP=10) with 3 more long exposures, undithered, in the central position to increase depth and to test the effect of no dithering (i.e., pre-conditioning of the detector) including one exposure using sampseq=SPARS25. Another orbit (visit 1) observed the same field in 2 filters with the CCD's in WFC3-UVIS using F850LP (3 position dither, 3x360 seconds + a shallow 20 sec exposure for bright stars) and F775W (3 position dither, 3x360 sec + 8 sec shallow exposure), using FLASH=12 (to mitigate CTE). A similar set of F850LP and F775W observations were obtained of the field with ACS WFC (visit 2).

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<sup>1</sup> Experiments to overcome this limitation by dropping to gyro control were attempted in the same calibration program but the much higher level of Earth light reached (hundreds of e/sec) came with large and uneven spatial variations that produce systematic uncertainties in the stellar photometry which were larger than the CRNL effect. Gyro drift enhanced this problem by spreading the PSF and producing a differential, systematic error between the gyro-guided exposures (with bright limb light) and the FGS exposures without. Another experiment used the WFC3 lamp during observations in the hopes that the lamp light reflected from the baffles would produce a high level of background, but the baffles are too efficient at absorbing the lamp light for this configuration to be useful.

We used the combined depth of the WFC3 F850LP observation,  $t=1080$  seconds, to produce a master star list using the DAOfind algorithm to find unresolved sources. From this list we selected only well-isolated stars by identifying those without a companion. (A companion was defined as a star within  $0.4''$  and down to 3.0 mag fainter or within  $2.0''$  and more than 4 mag brighter.) This produced a list of 1457 stars down to F850LP=22 mag (signal-to-noise ratio  $\sim 40$ ). Figure 1 shows a small region of the field in the UVIS and NIR. To increase the dynamic range we added to this list 3 very bright stars, F850LP=12-14 mag, which were not saturated in the short, shallow UVIS exposures. The positions of these stars were then identified in the CTE-corrected calibrated images (i.e., flc images) in the optical data and in the up-the-ramp, calibrated near-IR images (flt images). We then multiplied the images by the pixel area maps and measured small aperture photometry ( $r=5$  pixels or  $0.2''$  for WFC3-UVIS,  $r=2$  pixels or  $0.26''$  for WFC3-IR) of the stars using the standard zeropoints and a sky annulus of  $2''$  (inner) to  $2.4''$  (outer).

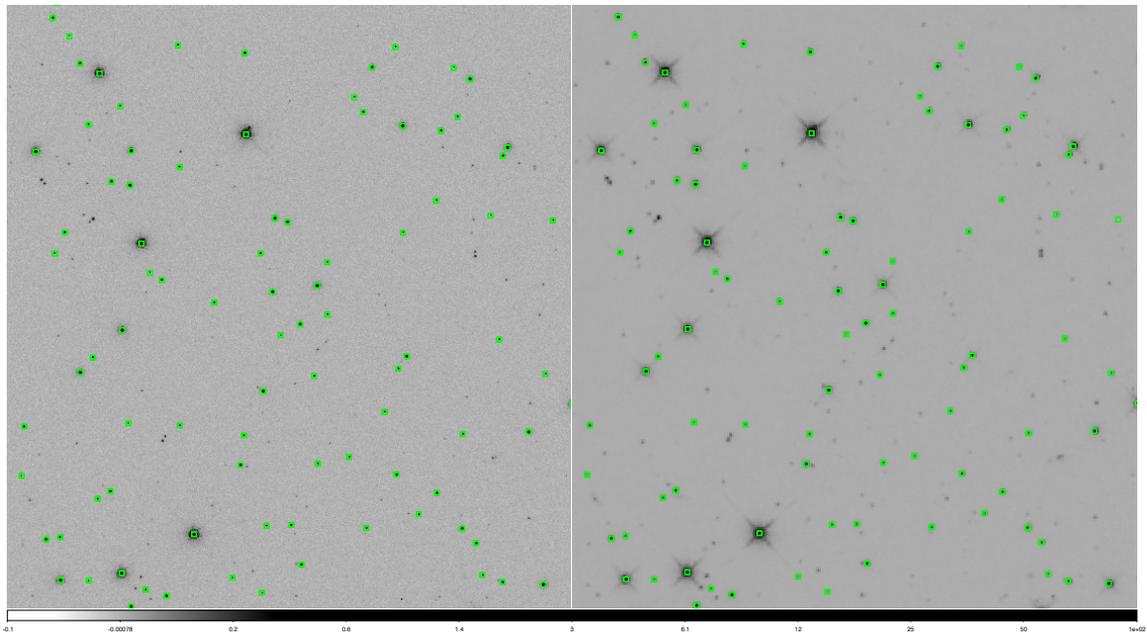


Figure 1: A small region of the target field  $6'$  West from the core of 47 Tuc, WFC3-UVIS F850LP on the left, WFC3-IR F098M on the right. The measured stars are marked with green boxes.

Following the same procedure used in Riess (2010), we compared the magnitudes measured in WFC3-UVIS F850LP to those in WFC3-IR F098M, filters with large wavelength overlap, using the measurement of their F775W-F850LP colors to account for their SED-dependent differences. We made an initial estimate of the linear relationship (i.e., color term) between the WFC3 F775W-F850LP and F850LP-F098M colors using stellar isochrones with  $Z_{\text{initial}}=0.003$  and Age=13 Gyr

calculated by the Padova group (Parsec 3.0, Girardi et al. 2018). These are shown in Figure 2 (upper, left) where a slope of  $0.28 \pm 0.04$  mag of F850LP-F098M per magnitude of F775W-F850LP is seen to be a good match for stars in the color and expected magnitude range for 47 Tuc. The useful, measurable range of  $12 < \text{F850LP} < 22$  mag for stars will include K-Giants (main sequence turnoff at F850LP  $\sim 17$  mag) and main sequence stars of spectral types K and early M-dwarfs which will have  $0.8 < M_{\text{ini}} < 0.3$ . Taking the difference between F850LP and F098M and accounting for the color term reveals evidence of a small tilt with magnitude of the size and direction expected for the CRNL. We perform a formal  $\chi^2$  minimization to determine the CRNL making use of the photometry errors and the initial estimate of the color term with an 0.04 mag uncertainty.

Following Riess (2010) we define

$$\mathbf{z} = a_0 \mathbf{y} + a_1 (\mathbf{i} - \mathbf{z}) + a_2 \quad (1)$$

where  $\mathbf{z} = \text{F850LP}$ ,  $\mathbf{i} = \text{F775W}$  and  $\mathbf{y} = \text{F098M}$  are vectors of magnitudes and  $a_0, a_1$ , and  $a_2$  are free parameters. To this we add the constraining equation

$$a_1 - a_1' = 0, \quad \sigma = 0.04 \quad \text{where } a_1' \text{ is the initial estimate of the color term based on the stellar isochrones.}$$

The residuals to the best fit vs  $z$  and  $i-z$  color are shown in Figure 2. Overall the  $\chi^2$  is good although there are a few regions in magnitude space where there may be some correlations of residuals. Because certain magnitudes correspond to similar spectral types, these correlated residuals likely result from inadequacy of the assumption of a linear color term for specific SEDs. We find  $a_0 = 0.9960 \pm 0.00094$  which transforms to  $2.5(a_0 - 1) = 0.0099 \pm 0.0023$  mag/dex. This agrees well with the result of  $a_0 = 0.9955 \pm 0.0012$  ( $0.011 \pm 0.0031$  mag/dex) found in Riess (2010) *but there is a ~50% improvement here in precision*. The consistency is reassuring considering important differences in approaches; Riess (2010) used F850LP mags from ACS as the reference flux scale, the color was F550M-F850LP, the observations were obtained 8 years earlier (2009 vs 2017) and the stars were bluer as they came from the open cluster NGC 3603. The new observations also span a much greater dynamic range of 10 mag, 12.5-22.5 mag (vs 4, 15-19 mag in Riess 2010). Increasing the aperture size for the WFC3-IR images from  $r=2$  to  $r=3$  has little impact, reducing the CRNL from 0.0099 to 0.0096 mag/dex.

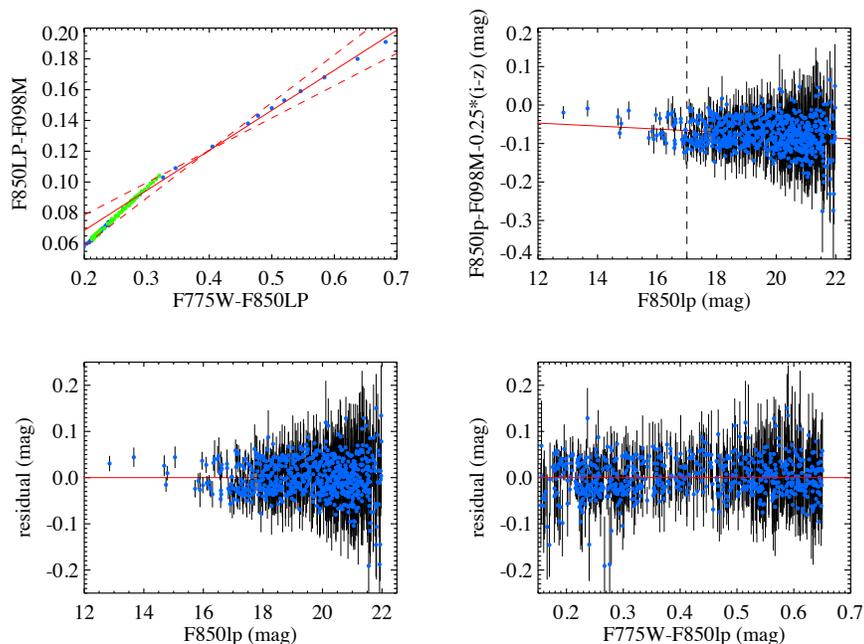


Figure 2: Upper left, F775W-F850LP vs F850LP-F098M synthetic relation determined from stellar isochrones (Parsec 3.0) with  $Z_{\text{initial}}=0.003$  and Age=13 Gyr (green=Giants;  $\log g < 3$ , blue=dwarves;  $\log g > 3$ ). Red line indicates our initial estimate. Upper right, difference between WFC3-UVIS F850LP and WFC3-IR F098M corrected for color-dependent difference vs F850LP magnitude where the tilt reveals the CRNL. Lower, residuals from the fit of the CRNL,  $0.0099 \pm 0.0023$  mag/dex, vs magnitude (left) and color (right). Red line shows zero residual. Some clustering of residuals results from limitations of linear correction for SED

## White Dwarf Spectrophotometric Sequence

An independent (and unanticipated) measurement of the CRNL is available by comparing the expected and measured photometry of a set of 18 hot ( $T_{\text{eff}} > 20,000$  K) DA white dwarf (WD) from the program by Saha et al. (GO 12967, 13711). Such white dwarfs have atmospheres which are almost pure hydrogen and their photospheres are purely radiative making their SEDs the simplest of all stars to model, with opacities known from first principles. The intrinsic DA WD SED can be described by only two parameters, temperature and surface gravity and these can be measured from spectra (i.e., independent of extinction) through a fit to the Balmer line profile. Matching the constrained SED to photometry measurements throughout bands in the ultra-violet and optical can well constrain two extrinsic parameters, extinction ( $\langle A_V \rangle = 0.12$  mag so  $\langle A_{F160W} \rangle \sim 0.02$  mag) and overall normalization (related to distance). The collection of the data and its analysis is well described in Calamida et al. (2019) and Narayan et al. (2019).

We excluded from analysis DA WD's known or suspected by Calamida et al. (2019) to be variable based on their photometric monitoring. Two other candidates showed evidence of binary contamination (Calamida et al. 2019 and Narayan et al. 2019) and were excluded: SDSS 41053 and SDSS 20372. Thus, 18 DA WDs with F160W 16.5-20.6 mag and the 3 HST primary CALSPEC standard WD's G191B2B, GD71 and GD153 (F160W 12.5-14.0) were analyzed. Binarity is an important consideration when comparing photometry to modeling and we consider this in detail in the appendix where we conclude it is not a factor in the present analysis.

To measure the CRNL in the one WFC3-IR band used to observe the DA WD's, F160W, we removed that band from the fit to the extinction and normalization, leaving the model fit to be constrained from WFC3-UVIS F275W, F336W, F475W, F625W and F775W. After constraining the two intrinsic and two extrinsic parameters, the expected magnitudes in F160W were compared to their measured values in Figure 3. Due to the very high quality and signal to noise of the photometry (mean  $\sigma_{F160W}=0.008$  mag) and the 8 magnitude dynamic range in flux of the data, the CRNL, expected to be  $\sim 0.02$  mag across the flux range of the WDs, is readily apparent. Because the photometry is tied to the HST photometric system through the observations and the model spectra of the three HST primary CALSPEC DA WDs, we fit a linear CRNL (same ways it has been previously measured for NICMOS and WFC3-IR) from the mean of the 3 standards (i.e., the CRNL is defined as zero for these) across the 18 DA WD's. We find a result of  $0.0059 \pm 0.0012$  mag/dex (similar to the  $0.0065 \pm 0.0013$  mag/dex found by Narayan et al. 2019), equivalent to a CRNL of  $0.99765 \pm 0.0005$ . This result is a bit closer to unity but consistent with the mean of all results without this measurement of  $0.99633 \pm 0.00045$  as seen in Figure 4.

Table 1: of WFC3-IR Count-rate Non-linearity Measurements

Photometry Source	Mag/dex	err	IR Filter	Mag Range	Reference
vs NIC2, stars in 47Tuc	-0.009	0.0022	F160W	16.0-22.0	Riess 2010
“	-0.010	0.0022	F110W	16.0-22.0	“
vs ACS-WFC, stars in NGC3603	-0.011	0.0031	F098M	15.0-19.0	“
Earth Limb, stars in NGC 1850	-0.01	0.005	F160W	21.0-24.0	Riess & Petro 2010
“	-0.01	0.005	F110W	21.3-24.3	“
vs 2MASS, asterisms	0.008	0.009	F160W	9.0-14.0	Riess 2011
“	0.003	0.006	F110W	9.5-14.5	“
vs WFC3-UVIS, stars in 47Tuc	-0.0099	0.0023	F098M	12.5-22.5	This work
vs ground, LMC Cepheids	-0.013	0.006	F160W	11.2-14.2	“
vs ground, MW Cepheids	-0.017	0.018	F160W	5.7-8.7	“
vs DA WD fitting	-0.0059	0.0012	F160W	14.0-21.0	This work, N19,C19
<b>Mean from All Photometry</b>	<b>-0.0077</b>	<b>0.0008</b>	<b>any</b>	<b>6-24</b>	
spectrophotometry, DA WD's	-0.0072	0.0008	Grism		Bohlin & Deustua 19
<b>All of the Above</b>	<b>-0.0075</b>	<b>0.0006</b>	<b>any</b>		

To extend the magnitude range over which CRNL has been measured to brighter magnitudes (i.e.,

< 12 mag) we have included two more data sets. The first is 46 Cepheids in the Milky Way whose photometry was measured with spatial scanning to be  $4 < F160W < 8$  mag by Riess et al. (2018). This can be compared directly to ground-based measurements in the H-band with relative dispersion of 0.048 mag (the dispersion results from variations in ground-based systems in the NIR). The CRNL across this range is measured to be  $0.9932 \pm 0.007$ . The result (see Figures 4 and 5). In addition, we compared photometry of 65 Cepheids in the Large Magellanic Cloud (10.5-14.5 mag in F160W) between F160W and the ground-based H-band (Riess et al. 2019) and derived a  $CRNL=0.9949 \pm 0.0025$  (Figures 4 and 5). Combining all of these measurements yields  $0.9969 \pm 0.00033$  which is  $0.0077 \pm 0.0008$  mag/dex from  $4 < F160W < 22$ . Fainter than 23<sup>rd</sup> mag photometry becomes sky dominated and the impact of CRNL is quenched. An independent corroboration of this result comes from a spectrophotometric comparison between the WFC3-IR grism and the combination of STIS spectra and models of DA WD's by Bohlin and Deustua 2019, in prep) which yields  $0.0072 \pm 0.0008$  mag/dex, similar to our result and also with no wavelength dependence. A combined result from these would be  $0.0075 \pm 0.0006$  mag/dex, see Table.

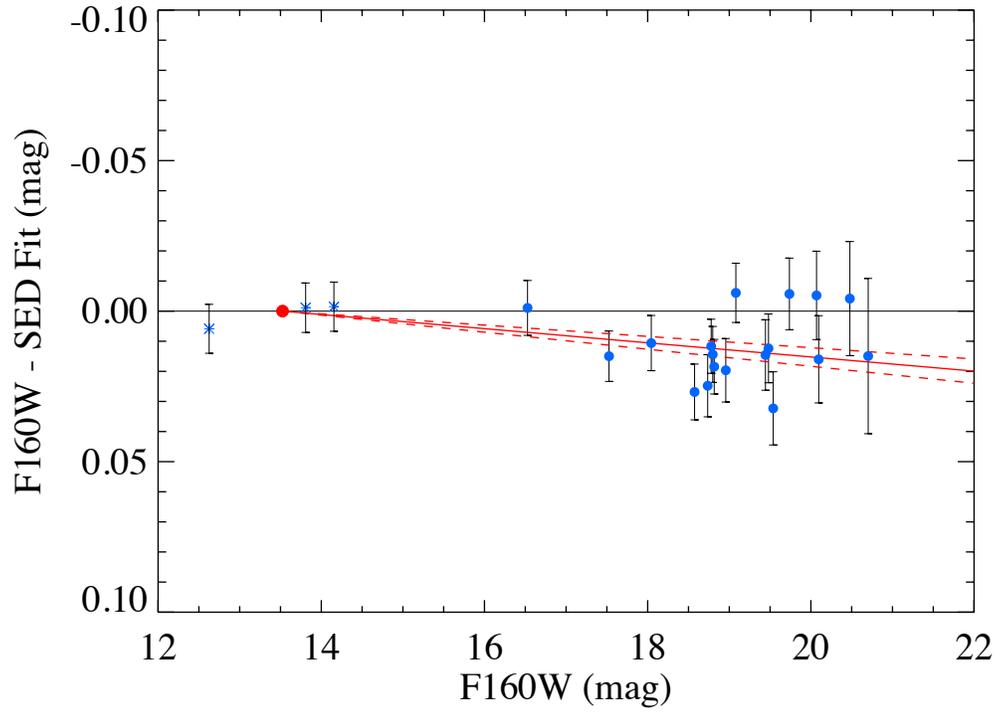


Figure 3: For 18 DA WDs from Saha et al programs (solid points) and 3 DA WDs used to set the HST zeropoints (asterisks), the difference between the observed and expected F160W magnitude (determined from SED model to from 5 bands blueward of F160W) versus F160W magnitude. The tilt results from the CRNL which is measured from this data as  $0.006 \pm 0.0012$  mag/dex.

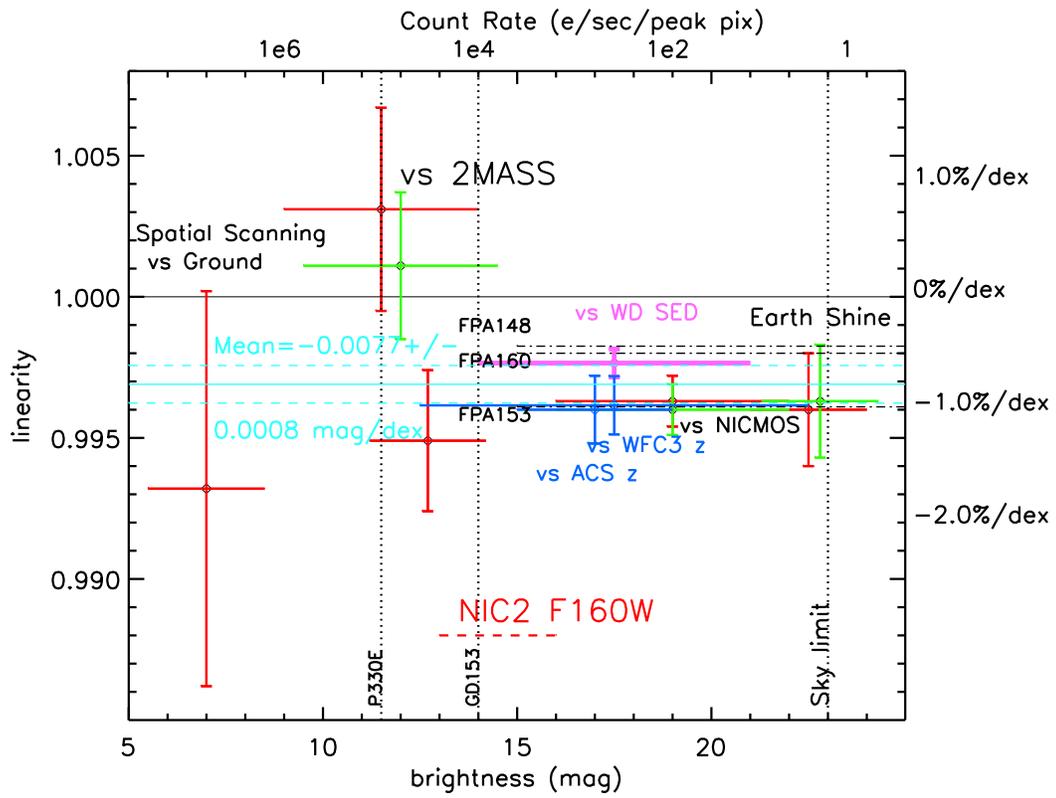


Figure 4: A summary of the CRNL for WFC3-IR photometry measured over 16 astronomical magnitudes from various sources described in the text.

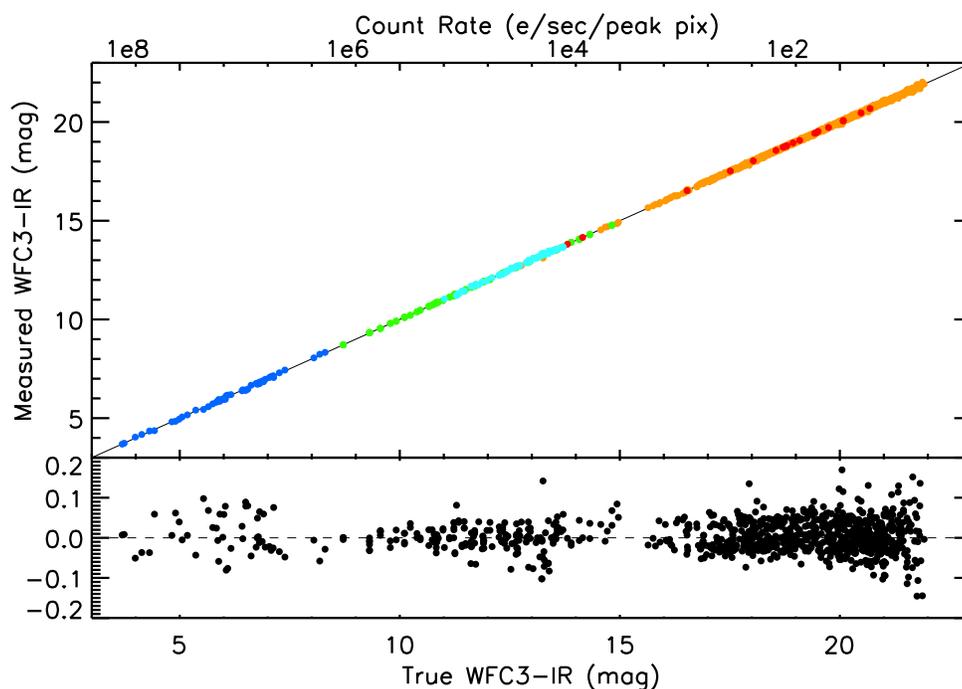


Figure 5: Magnitude ladder used to measure the CRNL for WFC3 over 16 astronomical magnitudes. Bottom plot shows residuals from the best fit  $0.0077 \pm 0.0008$  mag/dex result presented here.

## Conclusions

We find the CRNL in WFC3-IR to be  $0.0077 \pm 0.0008$  mag/dex (or  $0.0075 \pm 0.0006$  mag/dex including the grism measurements), characterized over 16 magnitudes with no apparent wavelength dependence and independent corroboration. This result may be used to correct IR photometry by using the difference in apparent flux (in dex) between where the WFC3-IR zeropoint is set ( $\sim 12^{\text{th}}$  mag) and the target source (fainter sources appear even fainter and thus are corrected to be brighter). One example application comes from the calibration of extragalactic Cepheids in SN Ia hosts using parallax measurements of Milky Way Cepheids, a range of 7 dex and thus a net correction of  $0.053 \pm 0.004$  mag, similar to the correction used in Riess et al.

(2018) but provided with greater precision here, and allowing, in principle, for a future 1% determination of the Hubble constant.

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## Appendix: Binarity

It is possible for the presence of an unresolved companion to contaminate the measurements of the WD fluxes in F160W, especially if the companion is of late-type (i.e., red) leaving it undetected in the visible but photometrically significant in the NIR. Here we consider the likelihood of this scenario from the known frequency of white dwarfs in binaries in nearby, volume limited studies. Toonen et al. (2017) studied the binarity of the fairly complete local white dwarf population (more than 100 WDs) within 20 parsecs comparing observations and binary population synthesis models. Assuming an initial binary fraction of 50% (consistent with general binary studies), a common outcome during the life of a WD in a binary is a common envelope phase (after Roche Lobe overflow) followed by a merger event with an expectation of 70% to 80% of observed WDs truly isolated by this late stage of evolution. This conclusion is well matched by the 78% in this state seen locally and also in the sample at somewhat larger volume ( $D < 25$  pc, Holberg et al. 2016). Of the 20% to 30% of WDs currently in binaries, most of these will be wider, resolved binaries as such binaries can more easily avoid the common envelope-merger phase. In the context of the local WD studies “resolved” generally means that a companion is bright enough to be seen and separated by more than a few arcseconds from the WD from ground-based images. This criterion is similar for the WDs from the Saha et al program. Although these are a factor of 10-50 times farther, HST’s resolution is 10-50 times better than the ground. Most problematic would be *unresolved* systems containing a WD and a Main Sequence star. Based on a wide range of the population synthesis models, Toonen et al. (2017) expect 0.5-1% of WD’s to be in such unresolved WDMS systems. This matches well the

empirical result that the local WD sample is comprised of  $\sim 0.4\%$  of these systems. Slightly more common, unresolved WD+WD systems (1%-4%) are less relevant to the present study since their more monochromatic excess flux would largely be removed with the grey (distance) term in Narayan et al. (2018).

We might expect an even smaller contamination fraction than from a complete sample due to the use of high signal-to-noise spectra to screen out companions. Narayan et al. (2016, 2018) reports the presence of a companion for one of the 23 WD systems, SDSSJ20372.169, apparent in emission in the trough of the WD H-beta feature where it should be most visible. Such emission can come from flares in late type stars. Because the typical visual absolute magnitude of the Saha program hot WDs is  $M_V \sim 9$  mag, M dwarfs with  $M_V = 10-15$  mag would be easily detected and removed in this way (even more so for earlier types). Only L dwarfs and early T dwarfs can “thread the needle” to evade optical detection and significantly contaminate the NIR mags which are  $M_H = 10$  mag (late T dwarfs and Y dwarfs are 5 to 10 mags fainter than the WD’s in the NIR and thus can be neglected). However, the range and level of contamination by such stars which have  $M_H = 10-15$  mag, is very broad, inducing an 0.01 to 0.5 mag contamination and thus would be expected to be readily distinguished from the consistently small,  $\sim 0.01$  mag level effect of CRNL in F160W. Indeed, there is one case of such apparent contamination in SDSSJ041053.632 which has a F160W fit residual of -0.68 mag, thus easily recognized and removed.

To summarize, binary contamination of the measurements of the CRNL should be very rare and readily distinguished in individual cases in the spectroscopy and photometric residuals. We conclude that the remaining WDs are free from such contamination.

It is also worth noting that binary contamination by a late type companion would *brighten* the observed WD, a photometric effect in the *opposite* direction to the CRNL which *dims* a WD’s NIR photometry. While this doesn’t rule out the possibility that *both* could occur, binarity alone can not cause the apparent CRNL signal presented here and as previously discussed binarity can be safely neglected for the sample of WDs analyzed here.