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An Independent Determination of WFC3-IR Zeropoints and Count Rate Non-Linearity from 2MASS Asterisms

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ABSTRACT We report the results from the CAL/WFC3 program 12335 to constrain the effect of count-rate non-linearity on the WFC3-IR detector by comparing the fluxes of 24 bright stars in asterisms observed with WFC3-IR and 2MASS. An incidental finding is an underestimate of the sample time of the first read for WFC3-IR (i.e., the zeroeth read) which is used to determine photometry for bright sources reaching saturation before the second read. After accounting for differences in zeropoint definitions and bandpass shapes, we find modest offsets of 0.02 +/- 0.01 mag at 1.2 and 1.6 microns between the two systems refelecting either the level of systematic uncertainty or a true but not very significant difference. The count-rate non-linearity is less than 0.01 mag per dex, consistent with previous findings.

Introduction

Traditionally, HST instruments have been calibrated through observations of a few spectrophotometric standards, setting the system throughput as required to match the expected fluxes through the entire optical path. Typically, pure hydrogen white dwarf stars and their observed Balmer line profiles have been used to model their spectral energy distributions and extend their empirical visual band calibration to other passbands. Comparison between the observed and expected magnitudes (using initial estimates of the instrument throughputs) are used to derive wavelength-dependent corrections to instrument throughputs. This procedure was applied to the newest imagers, WFC3 and ACS, resulting in corrections of 10% to 15% relative to ground testing across the sensitivity range . This approach offers a high precision calibration of HST as the spectral energy distributions of the spectrophotometric standard stars have been well-studied over the years. The drawback is that there is little data with which to test the accuracy of the method. Internal as well as external consistency is hard to evaluate with only a couple of stars.

The Two-Micron All Sky Survey (2MASS) yields uniform calibration of J,H and K stellar magnitudes to 15.9,15.0,14.3 mag, respectively, with signal-to-noise ratio > 10. Observations of bright stars in the 2MASS survey with WFC3-IR would provide the means to cross-calibrate the zeropoints of the two systems.

Another use of 2MASS photometry is as a reference for the measurement of detector count-rate non-linearity (hereafter CRNL; also known as reciprocity failure). The 2MASS photometry is sky-background dominated at J>14 mag and H>12 mag, reducing the dynamic range of the count rates of brighter star fluxes and reducing the effect of its own CRNL. We compare the dynamic range for a set of stars observed with both WFC3-IR and 2MASS to constrain the WFC3-IR CRNL.

Here we present observations of ~24 stars observed in WFC3/Cal program 12335, shown in Table 1, in the range of 8.5<J<14.5 mag and 9<H<15 mag and their analysis to test the WFC3-IR zeropoints and CRNL.

Observations

In order to insure the stars observed with WFC3 and 2MASS are not variable (or had spurious magnitudes), we selected stars which had been extensively observed in the infrared due their proximity to a variable object undergoing temporal monitoring. We selected these from the infrared AGN monitoring program of Gonzalez-Perez et al. (2001) and the Cepheid monitoring program of Monson and Pierce (2011

Observations used the two smallest subarrays which allow for fast readout to avoid saturation in the first read. For the RAPID read sequence and 64x64 or 128x128 pixel subarrays, the sample times are 0.061 and 0.113 seconds, respectively. We used the larger subarray for all stars fainter than J,H~9th mag, and the smaller subarray for the two stars with 8<J,H<9 mag.). [One program orbit in the ER AUR field failed due to loss of guide star lock and was repeated, providing an instance where 3 stars were measured at two different epochs.]

By selecting stars grouped within 1.5’x1.5’ we can repeatedly move between many of our targets without the overhead of a guide star reacquisition, allowing us to observe 2 sets of 3 star groups (with a single reacquisition between sets) in F125W and F160W (and a couple stars in F105W), with 2 dithers per filter as well as a pair of WFC3-UVIS exposures in F555W to verify the positions of the stars. Thus a single orbit was sufficient to observe 6 stars in 30 exposures with the whole program collecting 24 stars in 4 orbits for cross-calibration to 2MASS.

We reanalyzed the WFC3-IR monitoring data for the HST standard star P330E in order to determine the best reduction and analysis procedures for the asterism stars. We found that combining dithers into a single, resampled image (via multidrizzle) often resulted in the rejection of core pixels in the cosmic-ray rejection step due to the large sampling noise of the undersampled PSF. For such high-signal-to-noise data we found the best results were derived from aperture photometry on the flat-fielded images, using pixel area maps to account for the very small difference in pixel areas. Best results were obtained with an intermediate-sized aperture (r=5 pixels) and the use of an aperture correction derived from the median of the asterism stars from the r=5 aperture to 2" radii. The correction from 2" to infinity were taken from Kalirai et al (2009) to be 0.029 and 0.031 mag in F125W and F160W, respectively. This prescription resulted in an 0.01 mag dispersion among 24 observations of P330E, nearly identical to Kalirai et al. (2009). Comparison of the data quality arrays to the dithered photometry showed that flagged pixels rarely caused any significant change in stellar photometry. Spurious photometry due to bad pixels was identified through the combination of photometry which was discrepant in a pair of dithers and the presence of a flagged pixel near the star core. This occurred only once (one dither for star 20 in F125W).

Use of the vegamag zeropoints from Kalirai et al. (2009) for F160W of 24.70 resulted in a median measurement for P330E of 11.525 to 11.527 mag for a small (r=3 pixels) to large (r=2") aperture, in excellent agreement with the value of 11.525 mag expected from the spectrophotometry of P330E in *stsdas.synphot.calspec*. This is not surprising as P330E was one of two stars used by Kalirai et al. (2009) to determine the vegamag zeropoints we used (although our aperture corrections could have differed, that did not appear to be the case).

For F125W the vegamag zeropoint of 25.35 and the asterism-based aperture corrections resulted in P330E mags of 11.820 and 11.827 mag for the small and large aperture, about 0.01 mag *fainter* than the value of 11.813 expected from the spectrophotometry. This difference does not arise from a difference in aperture corrections as it persists at r=2" where the difference in aperture corrections becomes negligible. A small temporal trend in the data appears to cause a difference of ~0.004 mag between the first month of data (analyzed by Kalirai et al) and the rest which would reduce this difference by 40% but cause the same difference in the opposite direction if considered for F160W. Another source of difference is the averaging process between the two standard stars, P330E and GD153 for which zeropoints determined from each differs at the 0.5% level. Another source for potential differences comes from updates to the reference files (flat fields, pixel area maps) in the past two years as well as from different software and parameters. We will therefore assume a *systematic* uncertainty of 0.005 to 0.01 mag in the *application* of zeropoints to derive photometry. We do not know the origin of the 0.01 mag dispersion between repeated observations of P330E as it is about a factor of 3 times greater than the signal-to-noise in the data and does not appear to correlate with bad pixels. A reasonable guess would be that it results from the pixel-to-pixel flat fields, positional quantum efficiency (QE) variations within a pixel, or small temperature drifts to which QE is sensitive. We will assume a *statistical* noise floor of 0.01 mag per observation of an asterism star.

Reduction and preliminary analysis of the asterism data immediately revealed problematic flux measurements for a few of the brightest stars. In some dithers of the brightest stars, the peak pixel appeared to be anomynously bright, with a flux about 1.5 to 2 times expected (as seen from a radial profile of the star or from a successive dither). (Another clue was that the problem occurred in cases where the dither placed the PSF near the middle of a pixel, raising its count rate, *and* the saturation threshold was somewhat below the average). In these cases the calwfc3 pipeline indicated that only a *single* sample (known as the zeroeth read) was used in the accumulated sequence to determine the count rate of the pixel. In cases for which only a single unsaturated sample exists, it is not possible for the pipeline to determine the count rate from the change in counts (i.e., up-the-ramp-sampling) between samples. Rather, the pipeline is forced to use the total counts in the only unsaturated read (after subtracting a superbias and the dark current) divided by the time interval known as the zeroeth read interval (keyword=sampzero) which is 0.040 and 0.092 seconds for the small and larger subarrays we used. The consistency of this problem and subsequent tests of the pipeline (by H. Bushouse) indicates that the zeroth read time must be much larger than previously assumed. The source of this extra "overhead" time between detector reset and the first sample is not yet known. Its consequence for our program and others can be important because it brightens the magnitude at which saturation occurs from that expected by ~0.75 mag for the smallest subarray. For most of these cases we mitigated the issue by modestly raising the saturation threshold for these pixels (replacing the saturation threshold in the reference file wfc3ir_lin.fits[16] with 30,000 total counts). This results in the use of the ramp (i.e., at least 2 samples) to ~10% higher flux levels to determine the count rate and the use of the empirically determined non-linearity correction of ~5%. (Because the pixels remain sensitive, the flux level can be recovered by the use of a non-linear response curve). As the error in the non-linearity correction is a small fraction of the correction itself and the single pixel only a fraction of the total aperture flux, the net error for these few stars will be ~0.01 mag as verified by the consistency between pairs of dithers. An exception was star "ER AUR THREE" which was the brightest in the program with J=8.98 mag and H=8.57 mag, observed with the 64x64 pixel array. For this star, saturation reaches a factor of 25% in F160W and 60% in F125W by the time of the second read making the results unreliable and it was later rejected as a clear outlier star in the analysis.

One other anomalous star was observed. Star "3c66a 122" may be variable as it shows a dispersion of 0.06 mag in H (Gonzalez-Perez et al 2001) and its F160W measurements were rejected from the analysis. It was not observed in F125W.

Table 1: 2MASS Vegamag Photometry for Asterism Stars and HST Standards

Field	Star	J	err	H	err
ao0235	202	11.221	0.023	10.778	0.030
ao0235	204	11.905	0.021	11.616	0.032
ao0235	205	11.492	0.021	11.117	0.030
ao0235	208	12.917	0.024	12.326	0.032
ao0235	210	13.890	0.028	13.221	0.036
ao0235	211	12.693	0.023	12.306	0.034
ERAUR	FOUR	9.554	0.020	8.703	0.047
ERAUR	EIGHT	10.102	0.023	9.300	0.031

ERAUR	13	11.696	0.023	10.832	0.031
ERAUR	20	11.897	0.032	11.218	0.035
VXCYG	17	10.386	0.024	9.300	0.015
VXCYG	19	10.460	0.030	9.773	0.015
VXCYG	21	10.656	0.032	9.906	0.024
VXCYG	25	10.978	0.029	10.228	0.015
VXCYG	30	10.824	0.024	10.768	0.015
VXCYG	31	11.622	0.024	10.724	0.015
ERAUR	28	12.044	0.023	11.452	0.031
ERAUR	THREE	8.980	0.030	8.568	0.069
3c66a	116	12.960	0.023	12.640	0.021
3c66a	113	12.371	0.025	11.876	0.024
3c66a	112	14.817	0.039	14.307	0.057
3c66a	120	14.074	0.027	13.537	0.030
3c66a	119	11.248	0.022	10.860	0.021
3c66a	122	14.644	0.034	14.262	0.050
P330E	P330E	11.781	0.021	11.453	0.020
GD153	GD153	14.012	0.025	14.209	0.037
G191B2B	G191B2B	12.543	0.021	12.669	0.025
GD71	GD71	13.728	0.025	13.901	0.035

Analysis

In order to directly compare the photometry between 2MASS and WFC3-IR, it is necessary first to account for differences in their bandpasses and zeropoints.

Bandpass Differences

To account for bandpass differences, we derived synthetic color terms for stellar models over a suitable range in color for the 2MASS system and for WFC3-IR.

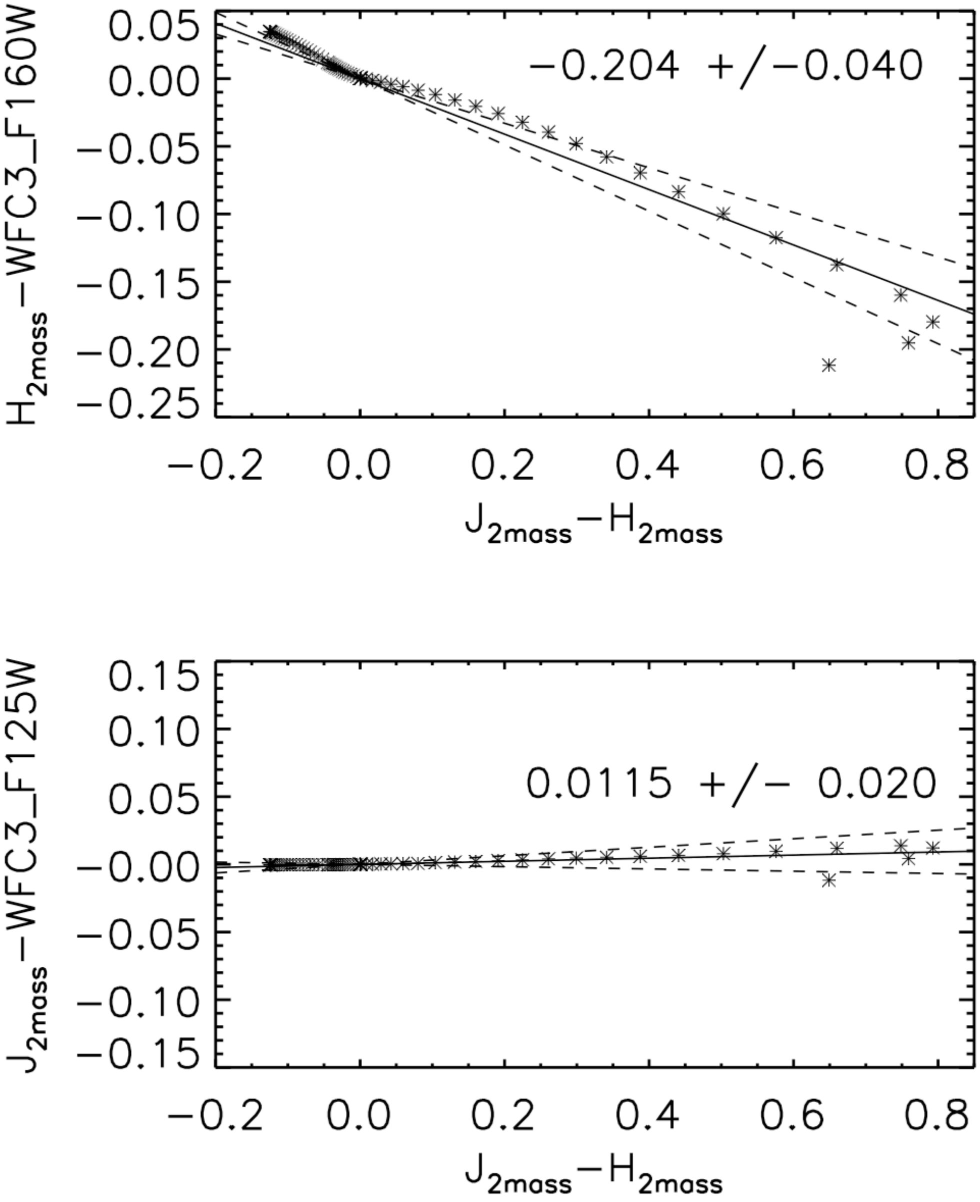

Figure 1. Synthetic color terms for 2MASS J and H versus WFC3 F160W (top) and F125W (bottom).

Following the same method employed in Riess (2010) we made a synthetic determination of the color terms between systems as a first guess before we fit for a correction to this guess based on the program stars.

We used the Castelli and Kurucz (2004) stellar models to determine the synthetic color terms. The models, available in the iraf library *stsdas.synphot.calcspec,* include stars with temperatures down to T=3500 degrees. We used those suitable for solar metallicity (Z=0.0 and gravity=g45) stars. The synthetic photometry was calculated using the iraf package *stsdas.synphot.calcphot* which includes the throughput of the telescope optics, instrument and filters. The 2MASS transmission functions were taken from the survey webpage and include atmospheric transmission (Skrutskie et al. 2006). The color term is defined as the magnitude difference in similar WFC3-IR and 2MASS filters divided by the 2MASS J-H color of the stars. The fits are shown in Figure 1 (solid line) and estimated uncertainty (dotted lines). The WFC3-IR F125W band is similar to the 2MASS J band with a small color term of 0.01 +/- 0.02 mag, but the WFC3-IR F160W is significantly bluer leading to a larger color term and uncertainty of -0.20 +/- 0.04 mag. These color terms and their uncertainties are included as a constraint to the global fit in the next section.

Zeropoint Differences

Although 2MASS and WFC3-IR (on the vegamag system) magnitudes are given relative to Vega, a small difference exists between the two surveys' estimations of the near-infrared brightness of Vega. The 2MASS zeropoints (Cohen et al. 2003) are set using the Vega model from Cohen et al. (1992) whereas the WFC3 vegamag zeropoints are defined relative to the Vega model spectrum matched to the HST STIS spectrum of Vega (Bohlin & Gililland 2004; hereafter BG) and extrapolated to the near-IR. The present version of the BG Vega spectrum is in the HST CDBS calspec database as "alpha_lyr_stis_005.fits". The difference between the two is 0.005 and 0.012 mag in 2MASS J and H, respectively in the sense that the BG spectrum of Vega is *brighter*. Hence, we would expect stellar fluxes measured by 2MASS to appear *brighter* by these amounts relative to WFC3-IR (everything else being equal).

Difference Fit

In Figure 2 we show the residuals between the 2MASS photometry (corrected for the different Vega zeropoint as given in the previous section) and the WFC3-IR photometry color corrected to the 2MASS system as discussed in the section preceding the last. The asterism stars are shown as diamonds, with 2 dithers per star (with the exception of the repeats of "13", "Eight", and "Four" in both bands and "20" in F125W resulting in a total of 4 exposures). The brightest star, "Three" (J=8.98 mag, H=8.56 mag), reached well into saturation in the second sample due to the unexpectedly interval preceding the zeroth read, was rejected as an outlier, and is shown with an "X" over its plotted points. The relative dispersion between the two system measurements is small, 0.022 mag between J and F125W and 0.017 mag between H and F160W which is smaller than even the mean of the given errors of the 2MASS measurements: 0.026 mag (the mean WFC3-

IR error of 0.006 mag is smaller than the 0.01 mag uncertainty we assume from the P330E stability measurements and contributes little to the quadrature sum of the uncertainties). However, the 2MASS uncertainties likely contain an assumed *systematic* uncertainty of ~0.02 mag (Skrutskie et al. 2006) included in quadrature and thus we would expect the given 2MASS uncertainties to overestimate the relative dispersion as observed.

Figure 2 appears to show a systematic difference between the two sets of measurements of size ~0.01 to 0.02 mag. While this difference may result from a zeropoint difference if could also arise from the CRNL or errors in the color corrections. Therefore we consider (simultaneously) contributions from a zeropoint difference, a residual color dependence (beyond the color correction we have made) and a non-linearity.

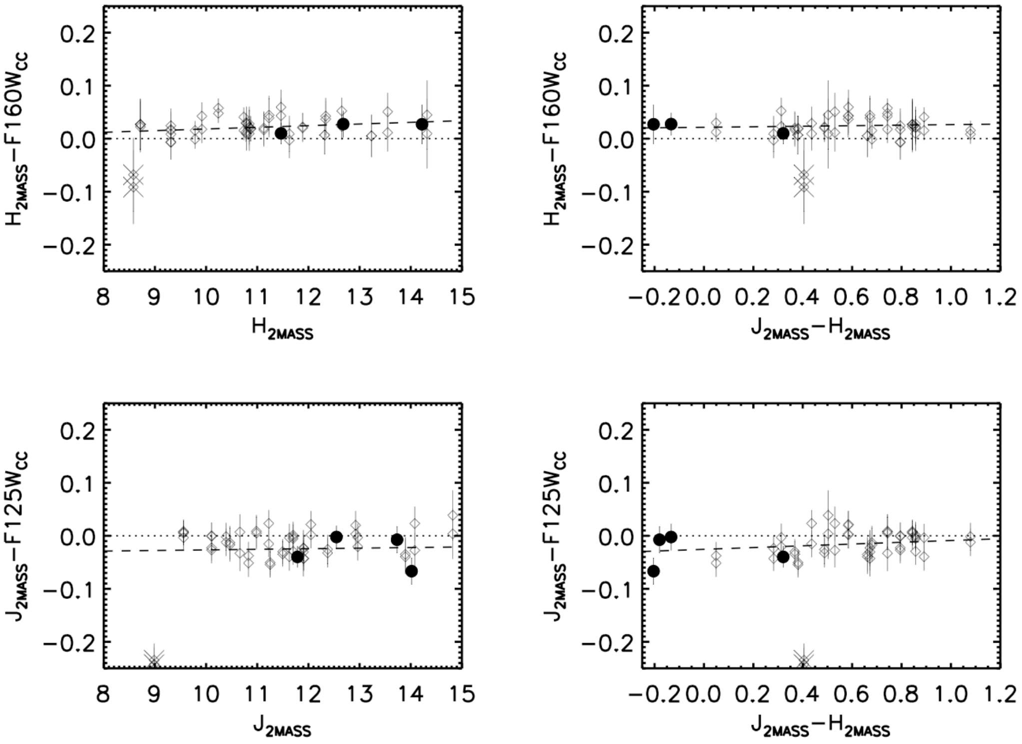

Figure 2: Photometric differences for stars between 2MASS and WFC3-IR. Asterism stars are shown as diamonds, HST standards as filled. The dotted line shows a straight line through zero residual and the dashed line shows the best fit to a 3 parameter (zeropoint difference, color residual, non-linearity) model of differences.

We describe these differences in equation 1. On the left are the array of 2MASS magnitudes in band x (after matching the Vega calibrations previously discussed). On the right are the corresponding WFC3-IR band mags, x', multiplied by a linearity parameter a_0 which should be close to unity, a residual color term Δa_1 multiplied by the 2MASS J-H color which should be close to zero, and a zeropoint offset, Δzp_x which should also be close to zero. The weights are given by the usual inverse product of the quadrature sum of the uncertainties in the photometry (WFC3 and 2MASS), accounting for the fully correlated error of the 2MASS mags for multiple dithers of the same star.

$$\mathbf{m\_x_{2MASS}} = \Delta zp_x + a_0 * (\mathbf{m\_x'_{WFC3}}) + \Delta a_1 * (\mathbf{m\_J_{2MASS}} - \mathbf{m\_H_{2MASS}}) \quad (1)$$

As in Riess (2010) we minimize the χ^2 statistic to find the best estimate of the free parameters (a_0, Δa_1,Δzp_x). To incorporate our prior constraint on the color correction determined from spectrophotometry (see Figure 1) we include the additional equation to the set in equation (1), $0 = \Delta a_1 \pm \sigma_{a1}$ where σ_{a1} is the uncertainty in the initial color correction for J and H, 0.02 and 0.04 mag, respectively.

Table 2: WFC3 / 2MASS	Δzp_x	a_0	mag/dex	Δa_1	Mean Dispersion (mag)	stars
F160W / H	0.0215 +/- 0.0054	1.0031 +/- 0.0024	-0.008 +/-0.006	0.006 +/- 0.008	0.0166	23
F125W / J	-0.0255 +/- 0.0063	1.0011 +/- 0.0026	-0.003 +/- 0.006	0.016 +/- 0.008	0.0211	22

Our asumed functional form of the non-linearity, is the same as De Jong et al. (2006), the true count rate, cr=flux$^{\alpha}$ where α=2-a_0 and flux is the observed flux.

The results are given in Table 2 with the parameters used to plot fits to the data in Figure 2. The most significant conclusions are small offsets in the zeropoints of 0.022 +/- 0.005 mag between F160W and 2MASS H and -0.026 +/- 0.006 between F125W and 2MASS J. While these offsets are formally significant at the 4σ confidence level this may be an overestimate due to the systematic uncertainty between the derivation and application of the WFC3-IR zeropoints discussed in the previous section whose size is similar to the statistical uncertainty in these offsets. Additional uncertainty may arise from either system in their use of additional sets of spectrophotometric standards other than Vega whose magnitudes relative to Vega are modeled but have individual uncertainties of about 0.01 mag as judged from the 9 examples in Bohlin and Cohen (2008). In this case the offsets are more accurately described as 0.02 +/- 0.01 mag in F160W/H and 0.025 +/- 0.01 mag in F125W/J. Thus either of two conclusions could be reached:

1) Zeropoint offsets of ~2% exist between WFC3-IR and 2MASS with ~95% confidence

or

2) The apparent 2% zeropoint offsets represent a ~2% systematic uncertainty in the knowledge of the near-IR zeropoints.

No significant non-linearity is detected with the two measurements consistent with none at the 0.5 and 1.2 σ confidence level for H and J, respectively. While this non-detection rules out the large non-linearity seen with the NICMOS detectors, it is more instructive to compare to previous calibrations. Figure 3 shows the present and past measurements of the WFC3-IR non-linearity as a function of the source brightness used for the measurement. The results are also compared to those seen for NICMOS (Bohlin, Lindler, Riess 2005) and for WFC3-IR flight spares tested in the Goddard detector lab. As compared to the earlier generation NICMOS detectors which exhibited CRNL at the level of 3% to 6% decrease in count rate per dex of decreasing flux, the WFC3-IR measurements indicate much smaller CRNL consistent with 1% or less per dex. These smaller values are consistent with what was observed with the flight spares. It is important to note that the Goddard measurements indicate a single value of CRNL which is specific to the detector and was determined at a range of count rates, 10,000 e/sec to 0.1 e/sec which are fainter than the present measurements or the flux from standard stars.

As an independent test we compared the WFC3-IR and 2MASS magnitudes for the HST standard stars P330E, GD153, G191B2B and GD71. The first two of these were used by Kalirai et al (2009) to determine the vegamag zeropoints for WFC3-IR, though newer data and reference files have been obtained since then. The standard stars are shown as solid points in Figure 2. The means of the standard stars are +0.02 +/- 0.015 mag in H/F160W and -0.03 +/- 0.015 mag in J/F125W, the same couple of percent offsets in the zeropoints relative to 2MASS seen for the asterism stars. For GD153 in J/F125W the difference is surprisingly large at -0.067 mag.

Do the present measurements suggest a change of sign of the CRNL at higher count rates? Taken at face-value, the two present measurements are 2σ and 3σ higher than the other measurements obtained at lower count rates. If the sign is really different one possible explanation could be *a degree of CRNL present in the 2MASS data*. The 2MASS observations become sky background dominated at J>14 and H>12 due to its large pixels, meaning that all of the J-band data and the brighter half of the H-band from 2MASS could suffer its own CRNL. The 2MASS survey used NICMOS3 HgCdTe detectors which exhibited substantial CRNL in the NICMOS instrument on board HST. If this was present in the 2MASS data it would invert the sense of the CRNL inferred from WFC3. As a test of this we cut the sample of stars to the fainter halves in J and H. For H, the CRNL term did invert around unity to 0.9986 +/- 0.0062 as compared to 1.0097 +/- 0.0052 for the brighter half, a 2σ change in the hypothesized sense. For J the opposite occurred with an increase to 1.0059 +/- 0.006 for the fainter half, compared to 0.99016 +/- 0.0052 for the brighter half. Its is hard to learn much from such a limited span of data but one may favor the H band results overall as providing a better test because the sky is 2 mag brighter allowing for a greater range of sky-limited (i.e., CRNL free) data from 2MASS. Taking the measurements at face value (i.e., without considering an uncalibrated CRNL for 2MASS), the results here would slightly change the extrapolated photometry from count rates where WFC3-IR zeropoints are determined to where sky-dominated sources are measured 0.03 +/- 0.01 mag too faint compared to the estimate of 0.04 +/- 0.01 mag from Riess (2010). However, even this change is not quite significant.

While uncertainties in the behavior of the WFC3-IR CRNL remain (and continue to be studied), the net impact to photometry of sources fainter than the sky level has been constrained through this and prior observations to the 1% level in flux.

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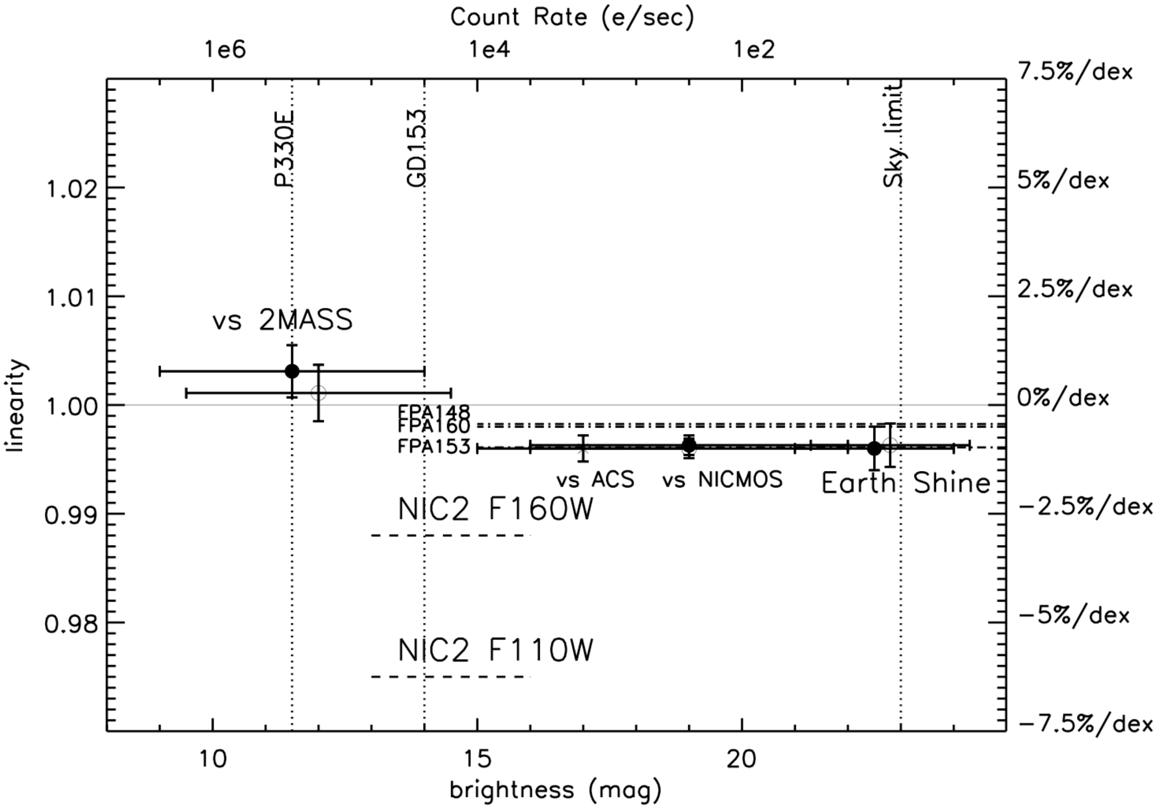

Figure 3: Comparison of assorted count-rate non-linearity measurements for WFC3-IR. The measurements reported here are labaled as "vs 2MASS" and those in Riess (2010) as "vs ACS" and "vs NICMOS". Those from Riess & Petro (2011) are labeled as "Earth Shin". Points determined from F160W are solid, from F125W are open circles and from F098M are open triangles. The values from the Goddard tested flight spares are indicated as "FPA" and those from NICMOS Camera 2 are indicated.

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