The 2010 STScI Calibration Workshop
Space Telescope Science Institute, 2010
Susana Deustua and Cristina Oliveira, eds.

The Photometric Performance and Calibration of WFC3

J. S. Kalirai and A. Rajan

Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD, 21218

Abstract. We analyze multiple observations of five bright HST spectrophotometric standard stars obtained with WFC3/UVIS and WFC3/IR in order to establish the temporal stability of the instrument over its first year of science operations and its photometric sensitivity. Observations of the five stars, GD 153, G191B2B, GD 71, GRW+70d5824, and P330E were obtained at multiple dither positions at each epoch in all filters. The cadence of the observations was once per week shortly after the instrument was installed in Hubble in the summer of 2009 (i.e., during SMOV) to once ever few months by the end of the first year. Analysis of the high signal-to-noise photometry in wide and medium-bands indicates that the instrument is photometrically stable, with measured variations that are <0.5%. As calibrated after SMOV, the absolute throughput of the instrument is substantially higher than predictions based on Thermal Vacuum 3 (TV3) tests. Preliminary photometric zero points have been calculated in UVIS and IR filters factoring in the measured on-orbit throughput, however this analysis still uses the WFC3 ground flat fields. A pending update will provide more accurate zero points based on the first on-orbit flat fields for WFC3 which have just been released.

1. Introduction and Background

Since its installation in Hubble in May 2009, the WFC3 instrument has quickly emerged as a powerful and unique tool for astrophysical investigations. The instrument offers two wide-field cameras that operate at high resolution and cover a broad wavelength range from the UV-visible-NIR (i.e., 200 – 1700 nm). A total of 77 narrow-, medium-, and wide-band imaging filters and 3 spectroscopic grisms on WFC3 ensure that a diverse set of scientific problems can be efficiently tackled. For example, during its first weeks of science operations, WFC3 captured images of an impact on Jupiter and also detected the highest redshift galaxies ever observed.

The success of scientific programs executed on WFC3 is intimately tied to the accuracy of the instrument's calibration. During the past year, many WFC3 calibration programs have been executed to establish the instrument's performance in orbit, several of which have the primary aim of characterizing the absolute sensitivity and stability of both the UVIS and IR cameras. The primary technique used to achieve the absolute calibration for HST instruments involves imaging bright spectrophotometric standard stars which have model spectral energy distributions that are well defined. For example, white dwarf stars contain pressure broadened Balmer lines that can be modeled to yield the temperature and gravity of the star in a non-degenerate way (e.g., Bergeron, Saffer, & Liebert 1992). The three primary spectrophotometric standards used by HST are the hot DA (hydrogen atmosphere) white dwarfs G191-B2B (V = 11.77), GD 153 (V = 13.35), and GD 71 (V = 13.03). For these three stars, the UV, visible, and NIR models agrees with the STIS spectra to better than 1%, indicating a superb absolute flux calibration. Further information on the calibration of these stars is provided in Finley, Koester, & Basri (1997), Bohlin (2000), and Bohlin, Dickinson, & Calzetti (2001).

In this paper, we describe the absolute calibration and photometric stability of WFC3 during its first year of science operations. Our goal is to provide a characterization of the end-to-end sensitivity of both instruments in all 77 imaging filters, taking into account the HST Optical Telescope Assembly (OTA) and instrument components such as the pickoff mirror, mirror reflectivity, inner/outer windows, detector quantum efficiency, and filter transmissions. Our final measurements are also dependent on the many other calibration reference files that are used to process _raw HST data into _flt and _drz images, such as the geometric distortion solution and the flat fields. At the time of this calibration workshop, an alpha-release geometric distortion solution was available however on-orbit flat fields were not, and therefore the "final" on-orbit sensitivity measurements are likely to change (at most) by a few percent in the near future.

2. The First On-Orbit Sensitivity Measurements: SMOV4

The expected performance of WFC3 was estimated from ground tests during Thermal Vacuum 3 (TV3), using the "CASTLE" optical stimulus at NASA/GSFC (see Brown 2008). The results of these tests led to throughput tables which were populated in CDBS and SYNPHOT, and from which photometric zero points were measured. We performed the first on-orbit calibration of WFC3's sensitivity shortly after the instrument was installed in Hubble. These first observations targeted GD 153 (one of the three primary spectrophotometric standards) on WFC3/UVIS1 in a subset of 37 widely used filters (based on Cycle 17 usage statistics). For WFC3/IR, we targeted both GD 153 and P330E (a solar analog secondary standard) in all 15 filters.

All of the exposure times were set to ensure a high signal-to-noise (e.g., $\sim$100) detection of the star, which typically required only a few seconds. The measured count-rate of these stars was compared to the predicted count rate from convolving the TV3 total system throughput with the model spectrum of the stars. Surprisingly, all of our results indicated that the true sensitivity of both cameras is much higher than the ground calibration indicates (see Figures 1 and 2). This is possibly due to uncertainties in the "CASTLE" calibration or alternatively, could represent an error in the throughput table of the HST OTA. We note that the first HST/ACS on-orbit measurements reported by Sirianni et al. (2002) were also systematically higher than their ground tests.

Details of our photometric technique and the methods used to calibrate the WFC3/UVIS and IR instrument throughputs based on these SMOV results are presented in two extensive ISRs, Kalirai *et al.* (2009a) and Kalirai *et al.* (2009b). We specifically note here that our first calibration from these results used an iterative approach where we compare synthetic photometry, as calculated after folding in a smooth correction to SYNPHOT, to the measured counts. The advantage of this approach is that SYNPHOT will take the integral of the actual bandpass with the full throughput, including the on-orbit correction factor, and will yield output photometry that then determines a new correction factor. The total system throughputs from this analysis were used to produce photometric zero points for WFC3 in the VEGAMAG, ABMAG, and STMAG systems, and updated throughput tables were calculated and installed in the CDBS (e.g., for SYNPHOT and the ETC) and OPUS pipelines. These zero points are also available on the WFC3 web page along with enclosed energy curves.

3. The WFC3/UVIS and IR Cycle 17 Calibration

At the conclusion of SMOV4, a more detailed WFC3/UVIS and IR calibration program was implemented to measure the total system throughput using multiple standard stars on both CCDs of the UVIS camera and the IR detector. Observations were also obtained in an expanded set of configurations (e.g., subarrays and full frames) and in those filters which were not observed in SMOV4. With knowledge of the on-orbit throughput, the exposure

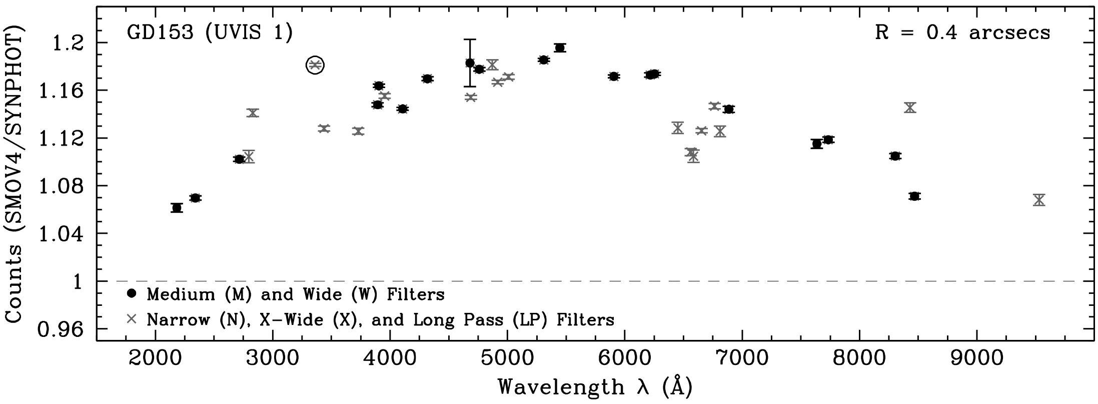

Figure 1: WFC3/UVIS measurements of a spectrophotometric standard star indicates that the total system throughput is 5 – 10% higher at blue and red wavelengths and 15 – 20% higher at 4000 – 7000 Å compared to ground tests.

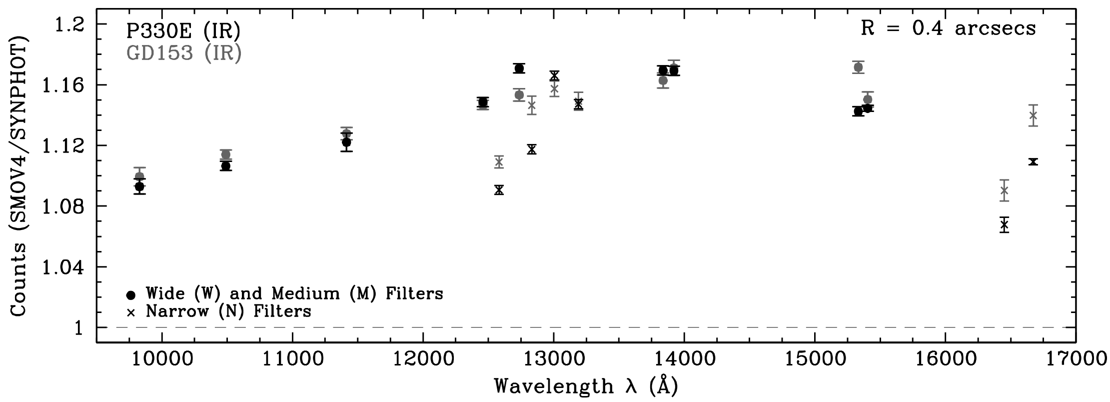

Figure 2: *WFC3/IR measurements of two spectrophotometric standards indicates that the total system throughput is 10 – 15% higher in all filters compared to ground tests.*

times in the Cycle 17 calibration program were adjusted to fill the full well up to 90% of its capacity (thereby minimizing the random errors in the photometry). All of these data, as well as the earlier SMOV4 observations, have also been reprocessed with updated calibration reference files.

3.1. Photometric Temporal Stability

The temporal stability of WFC3 can be characterized from the multiple data sets obtained throughout the first year of operation. A detailed discussion of the photometric stability will be presented in Kalirai et al. (2010, in prep), which will include an analysis of all spectrophotometric standards at multiple locations on each of the detectors. The observations with the highest S/N on the UVIS detector are those targeting GD 153, whereas the observations with the best cadence are those of the contamination monitor programs which target the HST standard GRW+70d5824 (CAL11426 and CAL11907). For the IR detector, observations of GD153 and P330E have a combined cadence of roughly once per month. To minimize systematics from spatially varying the location of the stars (e.g., flat field variations), we restrict our analysis to separate subsets of data taken at the same location of the detector. As one example, we illustrate in Figure 3 that the GD 153 observations observed on the 512 pixel UVIS1-C512A-SUB subarray indicate temporal stability to >99.5% over a 320 day time frame. Our measurements taken at the other corners of the UVIS detector with multiple standards also demonstrate that temporal variations are less than 0.5%, often limited by the error in the measurement. We also measure a similar stability on WFC3/IR in all wide and medium-band filters.

3.2. Towards New Absolute Throughput Measurements

The stability of WFC3 over its first year implies that the SMOV4 absolute throughput calibration of the instrument's UVIS and IR cameras is accurate. The calibration on the UVIS camera was based only on one star on one CCD, GD 153, whereas we have now observed G191B2B, P330E, and GD 71 on both CCDs. Similarly, for the IR camera, the calibration was based on both GD 153 and P330E and the other two stars have now been observed. Over the past year, several WFC3 reference files have changed (e.g., geometric distortion solution, bad pixel tables, dark, etc.), and so we have re-processed all of the SMOV4 and Cycle 17 data to re-measure the throughputs. Given the updated calibration to SYNPHOT based on the results shown in Figures 1 and 2, our expectation is that the measured counts of each of these stars will agree well with predictions from SYNPHOT.

We demonstrate the comparison between our aperture photometry and calibrated SYNPHOT predictions for WFC3/UVIS in Figure 4. Within each of the panels, the ratio of the measured to predicted counts is shown for a given standard, where all observations over multiple epochs have been averaged together. Observations in wide-band filters are shown with black open circles, narrow-band filters are in grey, and quad filters are in purple. All three of the stars show very similar trends with the ratios being near unity, as expected (the dotted lines mark $+/-2\%$ variations). Note specifically that observations in filters that deviate from unity, such as F336W or the red filters with $\lambda > 9000$ Å, are consistent among the three stars. These deviations were hinted in the SMOV4 data as reported in Kalirai et al. (2009b), however, we intentionally did not calibrate out the effects.

In Figure 5 (top), we present a closer comparison of the three standards shown in Figure 4 in wide-band filters. This plot demonstrates that the overall throughput of WFC3/UVIS is about 1% higher than indicated by the SMOV4 calibration. The bottom panel shows the residuals from comparing GD 153 to G191B2B (red curve) and GD 153 to P330E (blue curve). The large tick marks on this plot denote 0.5% variations and therefore the two white dwarfs are in exquisite agreement with one another. P330E falls slightly below the two white dwarfs, which is also what is seen for ACS (see Bohlin 2007). This likely indicates a small error in the flux calibration of the STIS P330E spectrum.

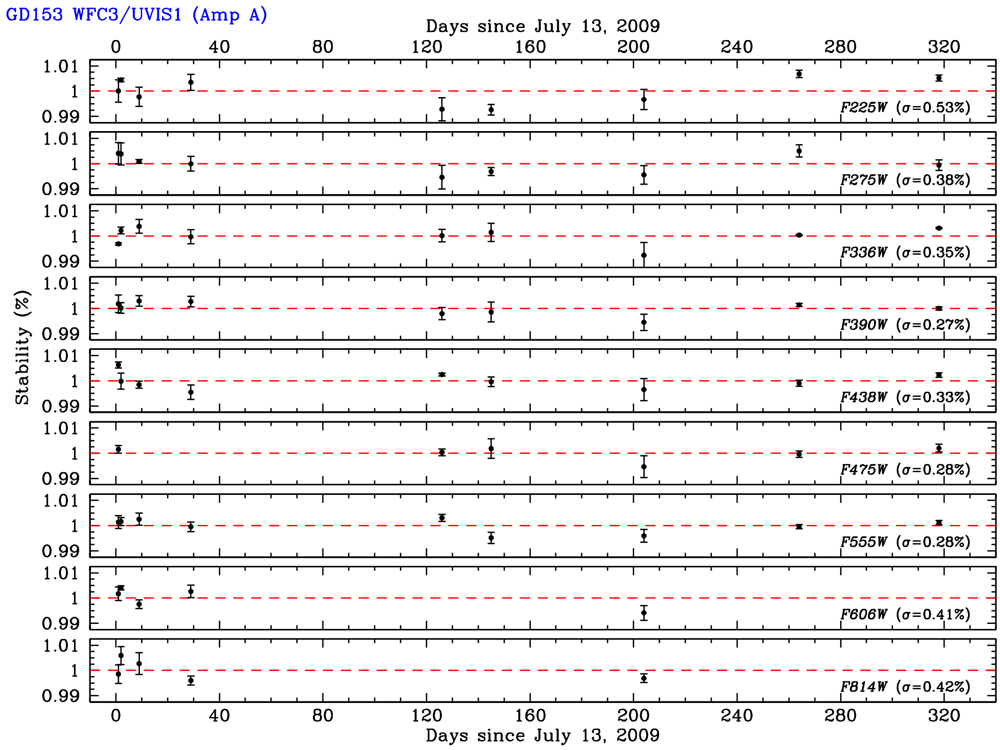

Figure 3: *The temporal stability of WFC3/UVIS as measured from higher signal-to-noise observations of the bright HST spectrophotometric standard GD 153 on UVIS1-C512A-SUB. At each of the epochs, four dither positions were obtained and averaged together, where the error bars reflect the 1σ error in the mean. All but a single wide-band filter (F218W – σ = 0.5%) shown here have standard deviations of <0.4% (note that the large tick marks represent 1% variations). Some of the observations in F606W and F814W shown in the bottom two panels were intentionally shifted to UVIS2 and are thus missing from the plot.*

A comparison of Cycle 17 observations of standard stars on WFC3/IR also shows very similar results to the SMOV calibration. Similar to Figures 4 and 5, our calibration indicates consistency at the 1% level between three white dwarfs (including GD 71) and the solar analog P330E, in all 15 IR filters.

For new instruments, the absolute throughput is expected to change as new calibration reference files are produced. The largest correction is often anticipated from the flat field, and preliminary tests with WFC3 suggest that low frequency spatial variations affect the ground-based flats causing photometric errors of several percent (see Sabbi et al. 2009). These ground flats are currently the calibration files in the OPUS pipeline and also were used to make Figures 4 and 5. The first on-orbit flat fields for WFC3 have been released in August 2010 on the instrument web page, and they have been shown to improve spatial variations by up to 4.5% in some filters, leaving much smaller residuals.

Of particular concern for the absolute throughput measurements is the quality of the flat field at the location of the subarrays in which the standard stars are placed. For the IR camera, the subarrays are located at the center of the detector and the new on-orbit flat agrees with the ground flat to within 1%. However, for the UVIS camera, the subarrays are located in the corners of the mosaic, and there are presently few overlapping observations that can provide a reliable correction at these extremes. This will improve as the flat field calibration program continues to execute through Cycle 18, and we will make corresponding updates to the WFC3 zero points and SYNPHOT throughput tables. At the present time,

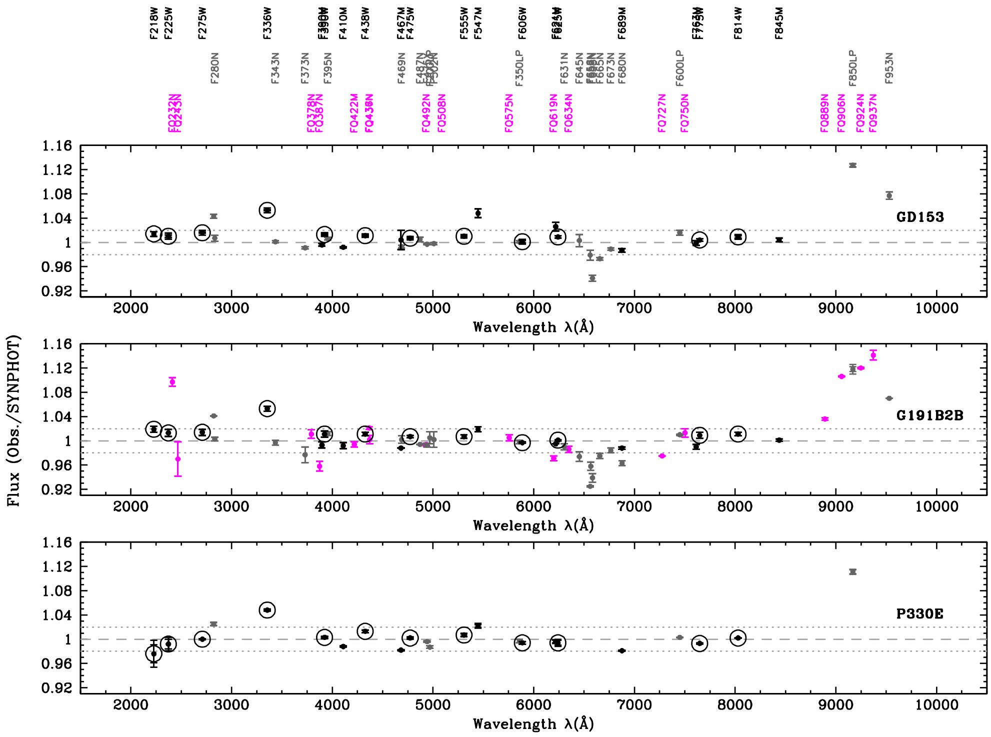

Figure 4: *A comparison of the measured counts vs post-SMOV4 calibrated SYNPHOT predictions for three standard stars. Observations in wide-band filters are shown with black open circles, narrow-band filters are in grey, and quad filters are in purple. All three of the stars show very similar trends and agree with the predictions to within 2% in most filters. As discussed in the text, an updated calibration that factors in these results will be performed after on-orbit flat are used to reprocess the data.*

it is important to note that the zero point of a filter such as F336W, which deviates from unity in Figures 4 and 5, is 5% higher than published.

4. Summary

The new WFC3 camera on Hubble is in full operation. The photometric throughput of the instrument's UVIS and IR cameras is calibrated to $\sim 1-2\%$ in almost every filter, which will improve even more when we apply on-orbit flat field corrections to the standard star observations. The overall sensitivity of WFC3/UVIS and IR is substantially better than predicted from ground tests, which will enable new scientific investigations and enhance others.

WFC3/UVIS has a higher throughput than any HST instrument over the wavelength range extending from its blue cutoff (at 2000 Å) to ∼4000 Å. Beyond this limit, the choice of which HST instrument is best suited for users depends on the details of the science requirements. Although the absolute throughput of ACS is higher at optical wavelengths, the highest WFC3 efficiency gains in our on-orbit observations also occur at 4000 – 7000 Å, and therefore the gap between the two instruments has been closed significantly. Specifically, some of the primary science observations with HST require several orbits where signal is coadded over multiple exposures. Relative to ACS/WFC, WFC3 has smaller pixels by 20%, a lower read noise by ∼50%, a smaller CTE correction, and a much lower dark current. Combined with our new efficiency measurements, the ability to better sample the PSF and naturally beat down the noise through multiple exposures can make WFC3 the

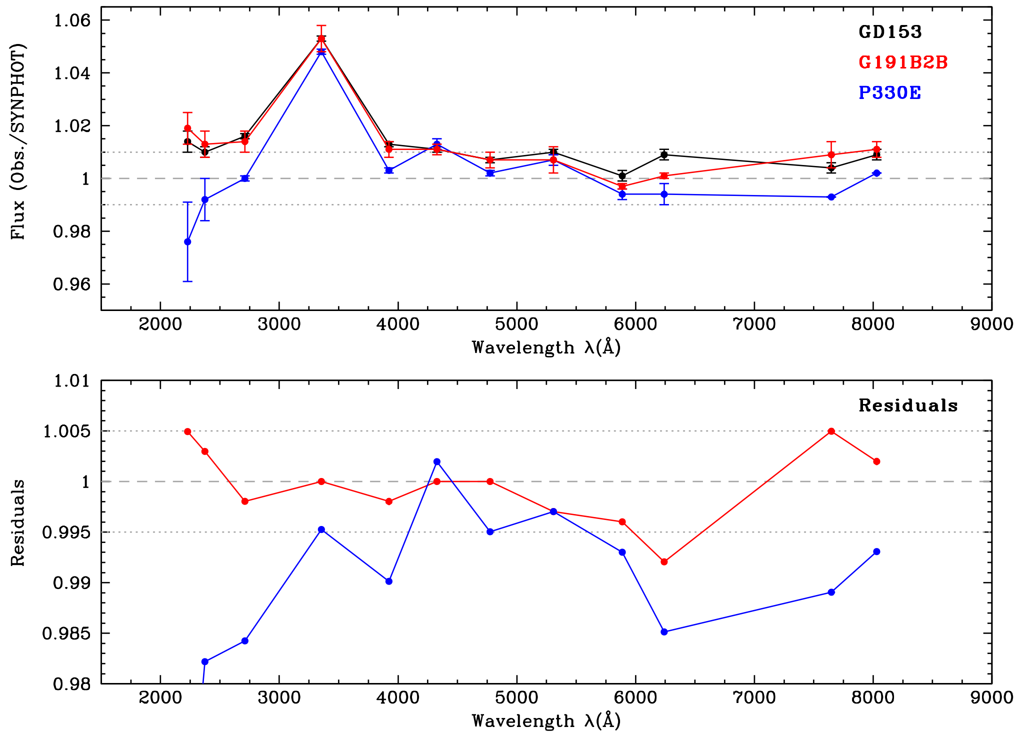

Figure 5: *A closer look at the measured counts of three standards in the wide-band filters and their SYNPHOT predictions. The curves for all three standards agree well with one another, with residual variations between the two white dwarfs being <0.5%.*

preferred instrument for even broadband F606W and F814W observations of faint sources. For example, the two instruments will both reach a limiting ABMAG of 27.9 (29.2) for a S/N = 10 point source detection in 1 hour (10 hours) in the F606W filter. The choice between the two instruments will require careful predictions from the respective ETCs, factoring in the detailed observational setup. Of course, WFC3 contains many more filters over its complete wavelength range than ACS/WFC, yet ACS offers a 50% larger field of view, both considerations being potentially important for users.

References

Bergeron, P., Saffer, R. A., & Liebert, J. 1992, ApJ, 394, 228
Bohlin, R. C. 2000, AJ, 120, 437
Bohlin, R. C., Dickinson, M. E., & Calzetti, D. 2001, AJ, 122, 2118
Bohlin, R. C. 2007, ACS ISR 2007-06, "Photometric Calibration of the ACS CCD Cameras"
Brown, T. M. 2008, WFC3 ISR 2008-48, "WFC3 TV3 Testing: System Throughput on the UVIS Build 1' Detector"
Finley, D. S., Koester, D., & Basri, G. 1997, ApJ, 488, 375
Kalirai, J., et al. 2009a, WFC3 ISR 2009-30 (CAL11451), "WFC3 SMOV Proposal 11451: The Photometric Performance and Calibration of WFC3/IR"
Kalirai, J., et al. 2009b, WFC3 ISR 2009-31 (CAL11450), "WFC3 SMOV Proposal 11450: The Photometric Performance and Calibration of WFC3/UVIS"
Sabbi, E., 2009, WFC3 ISR 2009-19 (CAL11452), "WFC3 SMOV Program 11452: UVIS Flat Field Uniformity"

Sirianni, M., de Marchi, G., Gilliland, R. L., Bohlin, R. C., Pavlovsky, C., & Mack, J., 2002, HST Calibration Workshop, 31