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WFC3 TV3 Testing: IR Channel Throughput

Thomas M. Brown
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ABSTRACT

A new IR detector (IR4; FPA165) was housed in WFC3 in the recent campaign of thermal vacuum (TV) testing at GSFC. We performed measurements of the IR channel throughput and found that it exceeds by ~2-8% expectations from component measurements over the entire wavelength range of the channel. This is in contrast to the results of the first WFC3 TV test in 2004 and the second WFC3 TV test in 2007. In 2004, the first IR detector (IR2; FPA064) was in the instrument, and we found a grey deficiency of 15% in the measured throughput. In 2007, the second IR detector (IR1; FPA129) was in the instrument, and we found a deficiency that smoothly varied from about 2% on the blue end of its range to 20% on the red end of its range. At the component level, IR4 was already expected to be far superior to the previous two detectors (in QE and other parameters), so this finding amplifies that superiority. The throughput measurements in the current campaign were repeated several times with outstanding consistency (~1%).

Background

The Wide Field Camera 3 (WFC3) recently underwent ground testing in thermal vacuum (TV) conditions. A new IR detector (IR4; FPA165) is currently installed in the instrument, replacing the detector used during the 2007 TV tests (IR1; FPA129), which in turn replaced the detector used in the 2004 TV tests (IR2; FPA064). Both FPA165 and FPA129 are substrate thinned, in order to mitigate a potential issue with these detectors, wherein they produce elevated dark rates in response to cosmic ray impacts. This thinning process also enhances the quantum efficiency (QE) of the detector, particularly at blue wavelengths, but that QE enhancement varies from detector to detector. Before installation in WFC3, FPA129 was measured by the Detector Characterization Lab (DCL) at Goddard Space Flight Center to have significantly higher QE than FPA064 (which was not thinned), and FPA165 was measured to have significantly higher QE than FPA129 (even though they were both thinned).

Among the tests performed in TV is a measurement of the end-to-end throughput (i.e., the throughput of the entire instrument excluding the HST OTA). The current tests are similar to the tests performed during the first TV campaign (see Brown et al. 2005, ISR WFC3 2005-12) and the second TV campaign (see Brown 2007, ISR WFC3 2007-23). The throughput tests in 2007 suffered from an instability in the calibration of the optical stimulus (called “CASTLE”), making it appear that the WFC3 throughput was varying by tens of percent over the course of the campaign. That CASTLE instability was rectified on the last day of the 2007 campaign, allowing an accurate calibration of the throughput, but no sense of the inherent WFC3 throughput stability. In the current campaign, we have not had such problems with CASTLE, and the throughput results have been very repeatable.

Test Setup

For the IR throughput tests, WFC3 was illuminated with the CASTLE optical stimulus, which can deliver flux-calibrated monochromatic light to the WFC3 focal plane. We employed the 200 micron fiber on CASTLE, fed by a Tungsten lamp in combination with a double monochromator, producing a spot approximately 6 pixels across on the WFC3 IR detector. This large spot allows the throughput to be measured more accurately, because it averages over pixel-to-pixel variation in response and allows a large number of counts in the measurement (generally >> 10,000 electrons) without approaching the saturation limit of the IR detector (~100,000 electrons per pixel). For the standard throughput tests in the recent TV campaign (SMS IR11S82), the CASTLE bandpass was set to 10 nm, the CASTLE filters were set to ND5 (really ND4+ND1), and the CASTLE monochromator wavelength was scanned across the entire wavelength range of the channel, from 910 to 1650 nm, while WFC3 exposures were obtained in one of three filters (F110W, F140W, and F160W). On the UVIS channel of WFC3, there is a clear mode (i.e., with no filter in the beam) that can be used to characterize the throughput of the instrument independent of the filters; on the IR channel of WFC3, there is no clear mode, so the measurements in these three broad filters are the next best thing. The WFC3 exposures were taken as a RAPID sample sequence in the 512x512 subarray to avoid saturation. The filter/wavelength sequence was designed to track any systematic drifts in the CASTLE and to provide overlap in wavelength for each filter’s measurements. The exact scanning sequence was F110W (910, 970, 1050, 1150, & 1250 nm), F140W (1300, 1400, & 1500 nm), F160W (1550 & 1650 nm), F110W (940, 1000, 1100, 1200, & 1300 nm), F140W (1350 & 1450 nm), and F160W (1500 & 1600 nm). Each of these exposures was followed by a contemporaneous dark exposure using the same sample sequence and subarray. Although the dark rate is normally very small (especially relative to the source rate), these dark images also correct for any elevated dark rate (i.e., persistence) from previous illumination on the IR detector. As part of its initialization procedure, the CASTLE moves its ND filter wheel to the open position, which can over-saturate the WFC3 detector by orders of magnitude, causing persistence.

After the test was completed, the entire test was repeated with the CASTLE monochromator shuttered (SMS IR11S92). This companion test provided a measurement of the light leak in the CASTLE fiber, which would result in detected counts for WFC3 but would not be included in the CASTLE flux calibration (since it is chopped). The dark-subtracted images from the companion test were subtracted from the dark-subtracted images in the throughput run, thus correcting for the faint light leak in the CASTLE fibers; this correction has a discernible effect at the 1% level for the blue end of the IR channel wavelength range, and is negligible for the red end.

We ran SMS IR11S82 & IR11S92 three times with the instrument operating on its Side 1 electronics, and one time with the instrument operating on its Side 2 electronics. We also ran on Side 2 a throughput test encompassing the full IR filter set (SMS IR11S01B), along with its companion fiber leak test (SMS IR11S04). In earlier TV campaigns, we scanned all of the filters as part of the standard IR throughput test, but we later realized that it would be more accurate to use broad filters as the standard, with their smoothly varying transmission, instead of a filter set that includes the sharply-featured narrow-band filters. The filter transmission curves were measured very accurately before installation in the instrument, but uncertainties in the CASTLE wavelength calibration could potentially lead to systematic errors in the standard throughput test if it employed the narrow filters. For the full filter sweep (IR11S01B), the CASTLE was set to a 5 nm bandpass instead of a 10 nm bandpass, to avoid overfilling the bandpass of the narrow WFC3 filters, but this narrow CASTLE bandpass is subject to larger flux calibration uncertainties on the CASTLE reference detectors. Also, at the 5 nm setting, the illumination on WFC3 was significantly fainter, allowing the use of full-frame exposures without saturation.

CASTLE provides a photon flux using its own reference detectors, employing a Si photodiode at 1 micron and bluer wavelengths (the same reference detector used at the red end of the UVIS throughput tests), and an InGaAs photodiode at wavelengths above 1 micron. These reference detectors are far less sensitive than the WFC3 IR detector; thus, ND filters are inserted in the beam when illuminating WFC3, and removed from the beam when illuminating the CASTLE reference detectors. The WFC3 IR throughput measurements thus depend upon a calibration of these ND filters. The measured throughput is simply the count rate observed on WFC3 (electrons per second) divided by the flux measured by CASTLE (photons per second; provided in the "OSFLUX" header keyword), with the latter appropriately normalized to account for the ND filter transmission.

For the tests described herein, the commanded gain was 2.5 e^-/DN, but the actual gain is distinct from the commanded gain. There are 8 separate gain chains (1 for each detector quadrant, duplicated on each of the two electronic sides), and in principle they can each provide a gain that is slightly different than the commanded gain. All of the throughput tests were performed in quadrant 3. The preliminary analyses of the absolute gain tests on each side (B. Hilbert, private comm.) found quad 3 gain values of 2.65 and 2.60 on Sides 1 and 2, respectively, but it is much harder to measure absolute gain than it is to measure relative gain. Assuming the same gain on Sides 1 and 2 gives throughputs that differ by less than 0.1% (instead of the 2% difference found in those preliminary analyses), so we will assume the gain is the same on both sides. The gain analyses are ongoing, and the results at the time of this writing imply that the gain in quad 3 is somewhere between 2.5 and 2.7 e^-/DN; we will assume a gain of 2.6 e^-/DN. These gain calculations used the traditional mean-variance method, which does not correct for the interpixel capacitance (IPC); the IPC correction scales the gain by 0.87 (B. Hilbert & E. Malumuth, private communication), so we assume a gain of 0.87 x 2.6 = 2.26. Note that we can still achieve an accurate photometric calibration of WFC3 despite these gain uncertainties. In the end, one assumes a gain to convert DN to e^-, and then corrects the throughput curve to match the reference detectors on the ground and standard stars in flight. The uncertainty in the gain affects the statistical uncertainty that can be assigned to a photometric measurement, because that error bar comes from sqrt(e^-) instead of sqrt(DN), but the relationship between DN and absolute flux will not change with revisions to the gain.

The WFC3 images were processed with a minimal IDL-based pipeline that fits and subtracts the signal in the appropriate reference pixels (using 4 of the reference pixel columns along the left and right sides of the image), fits a line to counts vs. time in the non-destructive read sequence for each pixel in an exposure, and scales by the gain. The ramp fits for pixels within the CASTLE illumination spot were inspected on a read-by-read basis, and appear linear over the full read sequence to ~1% or better.

The source count rate detected by WFC3 in the processed images was measured using aperture photometry. The aperture radius was 20 pixels and the sky annulus spanned radii 20 to 30 pixels. The photometry thus has three levels of background subtraction (contemporaneous dark, companion images with CASTLE source shuttered, and sky annulus), with all of these corrections being extremely small, given the relatively high count rate in the source itself.

Results

The results for the standard (IR11S82) and all-filter (IR11S01B) throughput tests are shown in Tables 1 and 2, respectively, and plotted in Figure 1. The measured throughputs were extremely consistent in repeated runs, although there are small discrepancies between the results of the "standard" and "all filters" tests, presumably due to the difference in CASTLE bandpass (10 nm vs 5 nm) and the larger uncertainties of the CASTLE calibration in the latter case. Compared to the expected throughput (taking the product of the throughputs for the individual components measured before assembly), the measured throughput is 5-10% higher. This is in contrast to the previous TV tests in 2004 (when the detector was FPA064) and 2007 (when the detector was FPA129); each of those tests found a throughput deficiency with respect to expectations, with the 2004 throughput low by 15% at all wavelengths, and the 2007 throughput low by 2%-20% (smoothly varying from the blue end to the red end of the IR channel range). Given that all of the components aside from the detector are unchanged since the previous thermal vacuum tests, there are two possible explanations for this change in measured throughput with respect to expectations. First, it is possible that the DCL underestimated the QE of the current detector (FPA165) and overestimated the QE of the previous detectors (FPA064 and FPA129). Alternatively, it is possible that the change in throughput (relative to expectations) is due to systematic errors in the CASTLE flux calibration.

The WFC3 synphot files and IR ETCs have been assuming that FPA165 would show the same 2-20% throughput deficit found in the previous TV campaign. This assumption will be changed to reflect the results of the current TV campaign (i.e., a throughput surplus) sometime in the near future, with the ETC web page noting the change for users.

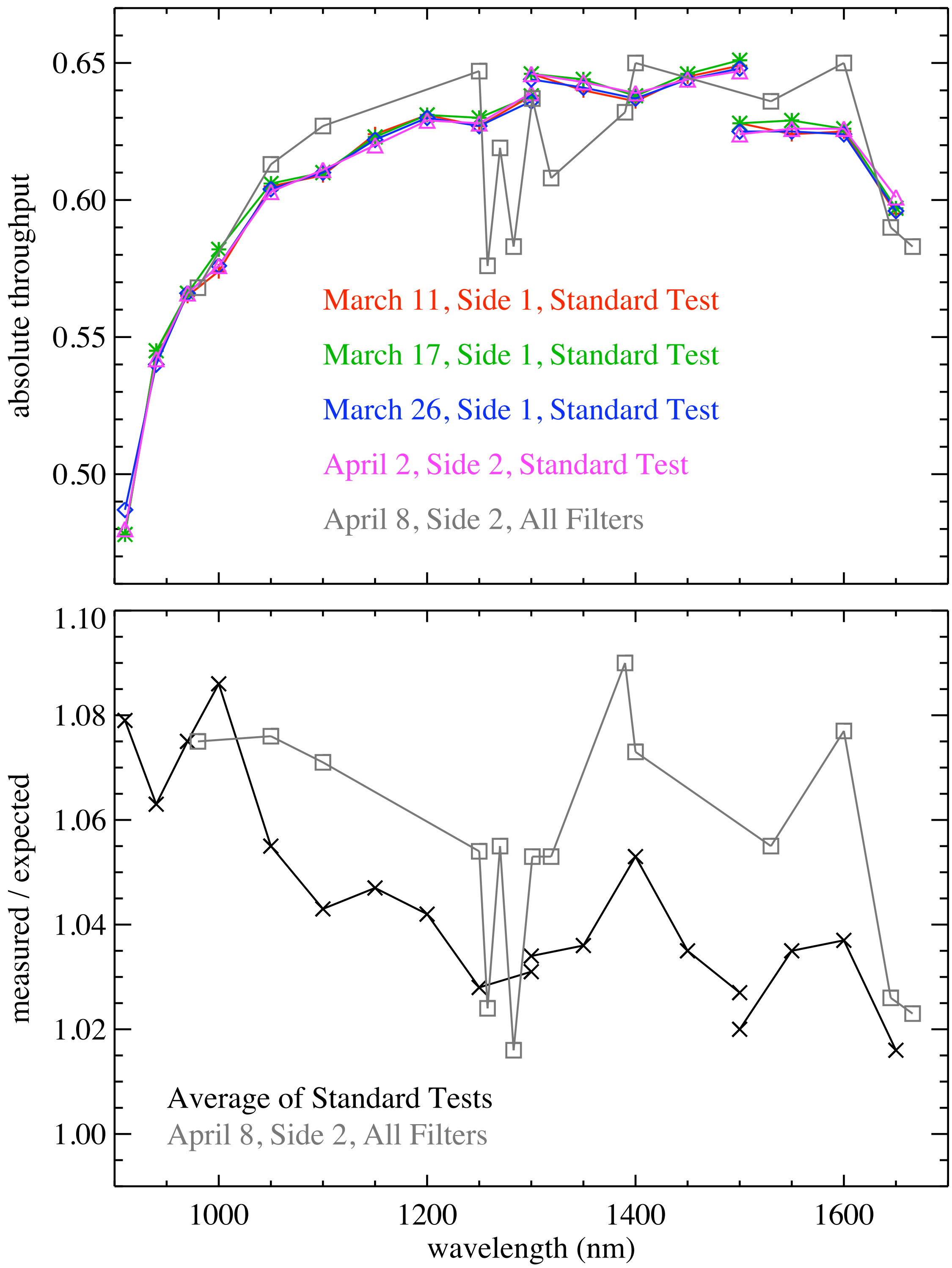

Figure 1: The absolute measured throughput from each of the throughput runs (*top panel*) and the measured throughput relative to the expectations from the component tests (*bottom panel*). The results of the standard tests are plotted with breaks in the curve where the filter is changed (F110W, F140W, & F160W).

Table 1. WFC3/IR throughputs measured in the "standard" throughput test (IR11S82)

filter	wavelength (nm)	throughput March 11 Side 1	throughput March 17 Side 1	throughput March 26 Side 1	throughput April 2 Side 2	Average throughput	measured / expected
F110W	910	0.478	0.478	0.487	0.480	0.481	1.079
F110W	940	0.545	0.545	0.540	0.542	0.543	1.063
F110W	970	0.565	0.566	0.566	0.566	0.566	1.075
F110W	1000	0.574	0.582	0.576	0.576	0.577	1.086
F110W	1050	0.605	0.606	0.604	0.603	0.605	1.055
F110W	1100	0.609	0.610	0.610	0.611	0.610	1.043
F110W	1150	0.624	0.623	0.622	0.620	0.622	1.047
F110W	1200	0.631	0.631	0.630	0.629	0.631	1.042
F110W	1250	0.627	0.630	0.627	0.628	0.628	1.028
F110W	1300	0.638	0.638	0.636	0.639	0.638	1.031
F140W	1300	0.646	0.646	0.644	0.646	0.645	1.034
F140W	1350	0.640	0.644	0.641	0.643	0.642	1.036
F140W	1400	0.636	0.638	0.637	0.639	0.638	1.053
F140W	1450	0.645	0.646	0.644	0.644	0.645	1.035
F160W	1500	0.628	0.628	0.625	0.624	0.626	1.020
F140W	1500	0.649	0.651	0.648	0.647	0.649	1.027
F160W	1550	0.624	0.629	0.625	0.626	0.626	1.035
F160W	1600	0.625	0.626	0.624	0.626	0.625	1.037
F160W	1650	0.595	0.597	0.596	0.601	0.597	1.016

Table 2. WFC3/IR throughputs measured in the "all filters" throughput test (IR11S01B)

filter	wavelength (nm)	throughput, April 8, Side 2	measured / expected
F098M	980	0.568	1.075
F105W	1050	0.613	1.076
F110W	1100	0.627	1.071
F125W	1250	0.647	1.054
F126N	1258	0.576	1.024
F127M	1270	0.619	1.055
F128N	1283	0.583	1.016
F130N	1301	0.637	1.053
F132N	1319	0.608	1.053
F139M	1390	0.632	1.090
F140W	1400	0.650	1.073
F153M	1530	0.636	1.055
F160W	1600	0.650	1.077
F164N	1645	0.590	1.026
F167N	1666	0.583	1.023