

WFC3 Optical Wavefront Error Characterization in Thermal-Vacuum Test #3

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26 August 2008

ABSTRACT

We have performed an assessment of the optical wavefront error of the WFC3 instrument in its final flight configuration, including the UVIS-1' and IR-4 detectors, during the 3rd thermal-vac test in March-April 2008. The measurements, including the additional WFE due to the OTA mid-frequency polishing errors, indicate that the CEI WFE specifications will be readily met on-orbit.

Introduction

The WFC3 CEI specification (STE-66) requires that the optical wavefront error (WFE) of the WFC3/OTA system, be less than specified values for each channel over the central half of the field (defined as the area inside the quadrilateral defined by the mid-points of the field edges), and below somewhat relaxed values in the four field corners; goal levels are also set. Using the WFC3 Optical Stimulus (CASTLE) as a stand-in for the OTA, we have assessed the WFE performance during the thermal vac #3 (TV3) testing in March-April '08. The CASTLE does not provide a perfect simulation of the OTA, but it has been repeatedly and redundantly been shown to match the OTA wavefront, in low-order Zernike terms, to within $\sim 0.017 \mu$ RMS (Greeley, 2003). Additional higher order WFE, due to zonal polishing errors in the OTA mirrors, must be added to our measurements to better predict the on-orbit performance.

Measurements

We have measured the WFE at 16 evenly distributed points over the field of each channel (Hartig, 2007) using phase retrieval (PR) analysis of images taken at several focus positions using scans of the CASTLE point source fiber Z stage. Images used in the analysis were obtained at fiber defocus settings of -35, -20, -10, 0, and +10 mm from nominal for each field position. The largest defocus corresponds to $\sim 2 \mu$ RMS, or 3.4 μ peak-to-valley (P-V). We used the PR algorithm originally developed by Burrows and

Krist at the STScI, adapted for use with WFC3, and previously used for evaluation and alignment of the ACS instrument. The measurements were made at 633 nm (HeNe laser source) for the UVIS channel with filter F625W and at 1060 nm (laser diode) for the IR channel with filter F105W. Prior to the measurements, the corrector mechanisms of both channels had been adjusted to optimize image quality, minimizing coma and defocus over the field and the PR measurements were made simultaneously with the alignment program; for details of the chronology, see Hartig (2008).

Figure 1 displays typical PR images for the IR (left) and UVIS (right) channels at the most extreme defocus. The upper image shows the pupil and model phase map, under which are displayed the measured and (noiseless) model images and a weighted difference image. Note the wider spiders, due to the IR cold mask and the 46% CASTLE central obscuration. The pupil rotation induced as CASTLE moves to off center V3 field positions is included in the PR analysis.

Results of the measurements made at both the cold and hot operate environments during TV3 are displayed in tables 1 and 2 (UVIS channel) and 3 and 4 (IR channel). Coefficients of the 13 low-order Zernike terms fit by the PR are listed in μ RMS, for each of the 16 field points, as well as the global mean, range and standard deviation for each term and the composite WFE. The small values of coma indicate that the corrector alignment was well adjusted to bring the CASTLE and WFC3 pupils into good registration and the corrector focus is also near optimal. The residual WFE is dominated by the field dependent astigmatism that is inherent in the WFC3 optical design together with a small amount of astigmatism due to CASTLE.

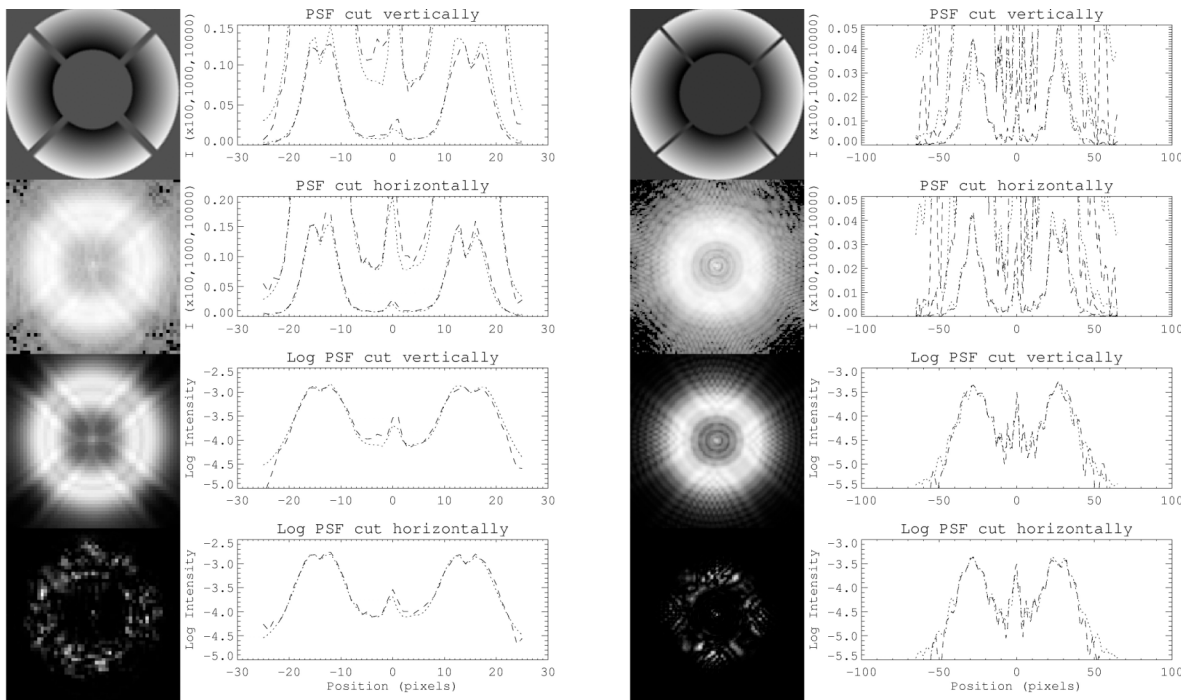


Figure 1. WFC3/IR (left) and UVIS (right) PR images at -35 mm CASTLE defocus

Table 1. WFC3/UVIS WFE Measurements in TV3 Cold Operate (μ RMS)

FPID	X(mm)	Y(mm)	RMS13	Focus	X-coma	Y-coma	0-astig	45-astg	sph-3rd	X-clovr	Y-clovr	X-spast	Y-spast	X-ashty	Y-ashty	sph-5th
uvzj01	-0.18	-2.97	0.044	0.011	-0.004	0.006	0.032	0.023	0.009	-0.003	0.002	-0.003	-0.002	0.000	0.000	0.008
uvzj02	-0.12	3.13	0.035	0.008	-0.002	0.002	0.030	0.011	0.011	-0.001	0.001	-0.003	0.002	0.000	0.000	0.006
uvzj03	26.89	-2.91	0.033	0.004	0.002	-0.006	0.018	0.025	0.004	0.001	0.001	-0.006	0.005	0.000	0.000	0.006
uvzj04	26.91	3.18	0.030	0.002	0.002	-0.009	0.016	0.018	0.007	0.002	-0.001	-0.007	0.006	0.000	0.000	0.007
uvzj05	-27.22	-2.98	0.047	-0.006	-0.001	0.003	0.042	0.010	0.016	0.002	0.001	0.001	-0.005	0.000	0.000	0.006
uvzj06	-27.19	3.12	0.046	-0.007	0.009	0.003	0.040	0.007	0.015	0.002	-0.002	0.000	-0.005	0.000	0.000	0.009
uvzj07	-27.25	-26.97	0.056	-0.011	0.002	0.006	0.052	0.012	0.012	0.003	-0.002	0.002	0.002	0.000	0.000	0.007
uvzj08	-27.10	27.07	0.050	-0.009	0.015	-0.005	0.036	-0.008	0.022	0.003	0.001	-0.007	-0.014	0.000	0.000	0.008
uvzj09	-0.24	-26.97	0.042	0.003	-0.007	0.001	0.030	0.025	0.003	0.001	0.000	0.002	0.006	0.000	0.000	0.008
uvzj10	-0.07	27.09	0.027	0.000	-0.003	-0.007	0.016	0.005	0.014	-0.003	0.005	-0.006	-0.005	-0.001	0.000	0.009
uvzj11	26.81	-26.88	0.042	-0.001	0.007	-0.014	0.021	0.030	0.000	0.000	0.002	-0.003	0.009	0.000	0.000	0.008
uvzj12	26.95	27.10	0.033	-0.016	0.002	-0.015	0.008	0.013	0.012	0.001	-0.001	-0.013	0.004	0.000	0.000	0.008
uvzj13	13.34	-13.42	0.038	0.009	-0.004	-0.001	0.026	0.023	0.005	-0.002	0.001	-0.003	0.006	0.000	0.000	0.006
uvzj14	13.41	13.63	0.030	0.004	-0.002	-0.004	0.019	0.015	0.011	-0.001	-0.001	-0.009	0.000	0.000	0.000	0.008
uvzj15	-13.72	-13.48	0.047	0.008	-0.005	0.008	0.041	0.015	0.010	-0.002	0.001	0.001	0.001	0.000	0.000	0.005
uvzj16	-13.63	13.60	0.034	0.000	-0.001	0.003	0.028	0.006	0.013	-0.005	0.001	-0.003	-0.003	0.000	0.000	0.009
Mean:			0.040	0.000	0.001	-0.002	0.028	0.014	0.010	0.000	0.001	-0.004	0.000	0.000	0.000	0.007
Range:			0.030	0.027	0.023	0.023	0.044	0.038	0.022	0.008	0.007	0.015	0.023	0.001	0.001	0.004
StDev:			0.008	0.008	0.006	0.007	0.012	0.010	0.005	0.002	0.002	0.004	0.006	0.000	0.000	0.001

Table 2. WFC3/UVIS WFE Measurements in TV3 Hot Operate (μ RMS)

FPID	X(mm)	Y(mm)	RMS13	Focus	X-coma	Y-coma	0-astig	45-astg	sph-3rd	X-clovr	Y-clovr	X-spast	Y-spast	X-ashty	Y-ashty	sph-5th
uvzl01	-0.19	-2.97	0.043	0.012	-0.005	0.009	0.031	0.021	0.006	-0.002	-0.001	-0.002	-0.002	0.000	0.000	0.011
uvzl02	-0.15	3.13	0.036	0.007	-0.005	0.006	0.029	0.014	0.011	-0.002	0.002	-0.003	-0.001	0.000	0.000	0.007
uvzl03	26.88	-2.91	0.035	0.004	0.000	-0.006	0.023	0.022	0.005	-0.001	0.003	-0.007	0.007	0.000	0.000	0.007
uvzl04	26.89	3.16	0.033	0.002	-0.003	-0.007	0.021	0.019	0.006	0.000	0.002	-0.010	0.006	0.000	0.000	0.007
uvzl05	-27.24	-2.98	0.047	-0.006	-0.004	0.009	0.041	0.006	0.017	0.002	0.000	0.002	-0.005	0.000	0.000	0.007
uvzl06	-27.22	3.12	0.043	-0.008	0.007	0.005	0.036	0.007	0.016	-0.001	0.000	0.002	-0.004	0.000	0.000	0.009
uvzl07	-27.28	-26.97	0.057	-0.013	0.002	0.013	0.051	0.012	0.013	0.003	0.001	0.003	0.000	0.000	0.000	0.007
uvzl08	-27.12	27.07	0.052	-0.008	0.017	-0.007	0.039	-0.009	0.021	0.002	0.002	-0.007	-0.013	0.000	0.000	0.007
uvzl09	-0.27	-26.97	0.043	0.004	-0.008	0.002	0.033	0.023	0.004	0.000	0.003	0.000	0.006	0.000	0.000	0.008
uvzl10	-0.09	27.09	0.024	0.000	-0.001	-0.009	0.013	0.001	0.014	-0.003	0.003	-0.006	-0.004	-0.001	0.000	0.008
uvzl11	26.77	-26.88	0.041	-0.002	0.003	-0.012	0.023	0.028	0.001	0.001	0.001	-0.004	0.010	0.000	0.000	0.007
uvzl12	26.94	27.10	0.030	-0.015	0.000	-0.014	0.005	0.006	0.012	0.002	-0.001	-0.012	0.005	0.000	0.000	0.008
uvzl13	13.30	-13.42	0.037	0.010	-0.005	-0.001	0.028	0.019	0.005	-0.002	0.002	-0.003	0.006	0.000	0.000	0.008
uvzl14	13.39	13.65	0.029	0.006	-0.003	-0.003	0.016	0.017	0.009	-0.002	-0.002	-0.008	0.000	0.000	0.000	0.009
uvzl15	-13.77	-13.48	0.045	0.007	-0.007	0.011	0.038	0.010	0.013	-0.001	0.002	0.002	0.001	0.000	0.000	0.006
uvzl16	-13.65	13.60	0.034	0.002	-0.002	0.008	0.028	0.000	0.013	-0.004	-0.001	-0.004	-0.003	0.000	0.000	0.009
Mean:			0.039	0.000	-0.001	0.000	0.028	0.012	0.010	0.000	0.001	-0.004	0.001	0.000	0.000	0.008
Range:			0.033	0.027	0.025	0.027	0.045	0.037	0.021	0.008	0.005	0.015	0.023	0.001	0.000	0.005
StDev:			0.009	0.008	0.006	0.009	0.011	0.010	0.006	0.002	0.002	0.005	0.006	0.000	0.000	0.001

Table 3. WFC3/IR WFE Measurements in TV3 Cold Operate (μ RMS)

FPID	X(mm)	Y(mm)	RMS13	Focus	X-coma	Y-coma	0-astig	45-astg	sph-3rd	X-clovr	Y-clovr	X-spast	Y-spast	X-ashty	Y-ashty	sph-5th
irzj01	1.78	-2.05	0.022	0.003	-0.008	-0.007	-0.004	-0.013	0.000	-0.002	-0.008	0.004	0.009	0.000	0.000	0.002
irzj02	-1.93	-2.05	0.033	0.022	-0.012	-0.015	0.001	-0.001	-0.002	-0.008	-0.009	-0.001	0.007	0.000	-0.001	0.002
irzj03	-1.93	1.66	0.027	0.001	0.003	-0.007	0.012	-0.019	-0.001	-0.001	-0.009	0.003	0.010	0.000	0.000	0.000
irzj04	1.76	1.67	0.024	-0.001	-0.008	-0.010	0.009	-0.014	-0.001	-0.001	-0.011	0.003	0.008	-0.001	0.000	0.000
irzj05	7.36	-7.61	0.049	0.001	-0.022	0.004	-0.035	-0.022	0.006	0.004	-0.009	0.004	0.004	0.000	0.000	0.002
irzj06	7.34	-2.05	0.028	-0.006	-0.016	-0.008	-0.006	-0.014	0.001	0.002	-0.009	0.003	0.008	0.000	0.000	0.000
irzj07	7.34	1.66	0.024	-0.005	-0.013	-0.008	0.005	-0.013	-0.003	0.001	-0.007	0.003	0.007	-0.001	0.000	0.002
irzj08	7.33	7.22	0.023	-0.008	-0.005	0.003	0.009	-0.014	-0.005	-0.002	-0.011	0.005	0.005	-0.001	0.000	0.002
irzj09	1.76	7.22	0.033	0.011	-0.003	-0.001	0.017	-0.019	-0.006	-0.002	-0.014	0.004	0.007	-0.001	0.000	-0.001
irzj10	-1.94	7.22	0.037	0.011	0.001	0.000	0.023	-0.021	-0.006	0.001	-0.013	0.003	0.009	-0.001	0.000	0.002
irzj11	-7.51	7.22	0.036	-0.012	0.007	0.009	0.019	-0.022	-0.002	0.002	-0.006	0.005	0.010	0.000	0.000	0.001
irzj12	-7.51	1.66	0.029	-0.014	0.009	-0.004	0.011	-0.017	-0.001	-0.002	-0.006	0.003	0.009	0.000	0.000	0.000
irzj13	-7.49	-2.05	0.026	-0.014	0.012	-0.005	-0.001	-0.010	0.000	-0.006	-0.006	0.004	0.010	0.000	0.000	0.001
irzj14	-7.49	-7.61	0.041	-0.007	0.019	0.010	-0.028	-0.002	0.007	-0.008	-0.006	0.002	0.012	0.000	0.000	0.000
irzj15	-1.93	-7.61	0.028	0.006	0.001	0.003	-0.024	-0.003	0.004	-0.001	-0.008	0.002	0.008	0.000	0.000	0.001
irzj16	1.78	-7.61	0.039	0.012	-0.009	0.003	-0.032	-0.010	0.003	-0.003	-0.006	0.003	0.008	0.000	0.000	0.004
Mean:			0.031	0.000	-0.003	-0.002	-0.002	-0.013	0.000	-0.002	-0.009	0.003	0.008	0.000	0.000	0.001
Range:			0.027	0.036	0.042	0.025	0.058	0.021	0.012	0.012	0.008	0.006	0.008	0.001	0.001	0.004
StDev:			0.008	0.010	0.011	0.007	0.019	0.007	0.004	0.003	0.002	0.001	0.002	0.000	0.000	0.001

Table 4. WFC3/IR WFE Measurements in TV3 Hot Operate (μ RMS)

FPID	X(mm)	Y(mm)	RMS13	Focus	X-coma	Y-coma	0-astig	45-astg	sph-3rd	X-clovr	Y-clovr	X-spast	Y-spast	X-ashty	Y-ashty	sph-5th
irzl01	1.76	-1.91	0.021	0.005	-0.006	-0.004	-0.007	-0.013	0.000	-0.002	-0.008	0.004	0.009	0.000	0.000	0.001
irzl02	-1.93	-1.91	0.019	0.004	0.005	-0.002	-0.002	-0.014	-0.001	-0.001	-0.006	0.004	0.009	0.000	0.000	0.002
irzl03	-1.94	1.80	0.029	0.003	0.003	-0.003	0.009	-0.022	-0.002	-0.002	-0.010	0.003	0.010	0.000	0.000	0.001
irzl04	1.78	1.80	0.022	0.002	-0.005	-0.005	0.007	-0.014	-0.002	0.000	-0.010	0.002	0.008	-0.001	0.000	0.001
irzl05	7.36	-7.47	0.048	0.000	-0.020	0.008	-0.037	-0.016	0.006	0.005	-0.009	0.004	0.003	0.000	0.000	0.002
irzl06	7.34	-1.91	0.025	-0.002	-0.014	-0.002	-0.009	-0.014	0.001	0.001	-0.009	0.003	0.007	-0.001	0.000	0.001
irzl07	7.34	1.78	0.020	-0.003	-0.011	-0.004	0.003	-0.012	-0.002	0.001	-0.007	0.003	0.007	-0.001	0.000	0.001
irzl08	7.33	7.34	0.023	-0.003	-0.002	0.007	0.006	-0.014	-0.005	-0.005	-0.011	0.004	0.005	-0.001	0.000	0.001
irzl09	2.12	7.36	0.033	0.012	-0.001	0.006	0.018	-0.017	-0.005	-0.002	-0.014	0.004	0.007	-0.001	0.000	-0.001
irzl10	-1.94	7.34	0.039	0.012	0.004	0.007	0.021	-0.022	-0.005	0.001	-0.015	0.004	0.010	-0.001	0.000	0.001
irzl11	-7.51	7.34	0.038	-0.012	0.009	0.014	0.018	-0.024	-0.002	0.003	-0.006	0.004	0.010	0.000	0.000	0.000
irzl12	-7.51	1.80	0.027	-0.011	0.010	-0.001	0.007	-0.019	-0.001	-0.003	-0.004	0.003	0.009	0.000	0.000	0.000
irzl13	-7.49	-1.91	0.026	-0.013	0.014	0.002	-0.002	-0.012	0.000	-0.006	-0.006	0.003	0.010	0.000	0.000	0.001
irzl14	-7.49	-7.47	0.042	-0.010	0.021	0.014	-0.027	-0.002	0.007	-0.008	-0.007	0.002	0.012	0.000	0.000	-0.001
irzl15	-1.93	-7.49	0.030	0.007	0.003	0.006	-0.026	-0.006	0.004	0.000	-0.007	0.001	0.009	0.000	0.000	0.001
irzl16	1.78	-7.49	0.038	0.010	-0.007	0.006	-0.032	-0.011	0.004	-0.003	-0.008	0.003	0.008	0.000	0.000	0.002
Mean:			0.030	0.000	0.000	0.003	-0.003	-0.014	0.000	-0.001	-0.009	0.003	0.008	0.000	0.000	0.001
Range:			0.029	0.025	0.041	0.019	0.058	0.021	0.012	0.013	0.010	0.003	0.009	0.001	0.001	0.004
StDev:			0.009	0.008	0.011	0.006	0.018	0.006	0.004	0.003	0.003	0.001	0.002	0.000	0.000	0.001

Discussion

In order to predict on-orbit performance, and comparison with the CEI specifications, the measurements presented above require addition of the WFE due to the OTA that is not simulated by the CASTLE stimulus. Krist and Burrows (1995) measured the mid-frequency WFE using PR analysis of a set of WFPC-2 images obtained at various OTA SM despace settings shortly after the first HST servicing mission. The resulting optical path difference “mirror map” is incorporated in our image modeling and amounts to ~ 0.018 μm RMS. Adding this (in quadrature) to the mean of the field points, exclusive of those in the field corners, yields the adopted prediction for the OTA/WFC3 field center WFE performance shown in Table 5 for each channel. The worst case field corner predictions are also shown. Both are well within the specification limits and meet or approach the goals at the measurement wavelengths (633 and 1060 nm).

Table 5. WFC3 WFE Prediction vs. Specifications (μ RMS)

		Req	Goal	Pred
UVIS	Center	< 0.054	< 0.047	0.048
	Corner	< 0.070	< 0.063	0.059
IR	Center	< 0.085	< 0.750	0.043
	Corner	< 0.111	< 0.100	0.051

The UVIS channel WFE performance in the UV may differ from that at 633 nm due to the presence of transmissive optical elements: two detector windows and the selected bandpass filter. Due to their proximity to the focal plane and the slow focal ratio ($f/31$), the windows are unlikely to contribute significantly to image quality degradation. The filters are located further from the focal surface, but the beam footprint subtends only 8-12 mm, depending on which wheel contains the selected filter. The transmitted WFE was measured for each UV filter (exception: no data were found for F336W) and shown to readily pass their RMS WFE specifications (< 0.02 waves @ 633 nm, measured in-band over the instantaneous FOV). The windows were also measured in transmission at 633 nm with excellent results $\leq .015$ waves rms @ 633 nm over the full aperture. These are excimer laser grade fused silica windows, so inhomogeneity and inclusions are minimal and the window contribution to the UV WFE at any field point should be quite small. Hence we may have confidence that the UVIS system WFE will also meet specification at all wavelengths on orbit.

Conclusion

We have performed an assessment of the optical wavefront error of the WFC3 instrument in its final flight configuration, including the UVIS-1' and IR-4 detectors, during the 3rd thermal-vac test in March-April 2008. The measurements, including the additional WFE due to the OTA mid-frequency polishing errors, indicate that the CEI WFE specifications will be readily met on-orbit. Although measurements were not made in the UV, the refractive elements of the UVIS channel are of high quality and are not expected to significantly degrade the effective WFE at any field point.

References

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Revision History

2009-04-19 – Revised format of tables 3 and 4 to enhance readability.