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WFC3 Flight Detector Alignment Characterization in Thermal-Vacuum Test #1

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ABSTRACT
We have performed an initial assessment of the alignment status of the UVIS-1and IR-2 flight detectors as mounted in WFC3 during the first instrument-level thermal-vac test. Both detectors are found to be aligned out of tolerance, indicating errors in the transfer of surrogate alignment information to the flight articles. Measurements made at various times through the thermal vac test, with the instrument in different thermal environments, demonstrate little variation. However, for reasons that remain unclear, the alignment of the UVIS detector, particularly its tilt about the X-axis, varied significantly in measurements made in ambient before and after thermal-vac testing. The UVIS-1 detector alignment must be modified to remove the residual alignment error. The IR-2 detector is not expected to fly; the measured alignment error must be used to set the alignment of the flight IR detector package, when it is completed at Ball Aerospace.

Introduction

The flight UVIS-1 CCD detector was installed in the WFC3 instrument in November 2003, after its mounting shims were adjusted at Ball Aerospace to incorporate residual alignment errors measured earlier with the UVIS surrogate detector. Likewise, the IR-2 detector was installed shortly thereafter, having been aligned according to measurements made with the bare MUX IR surrogate detector. While the alignment status of the IR detector could not be determined until the instrument underwent thermal-vac testing, that of the UVIS detector was checked shortly after its installation, in ambient, and found to be significantly out of tolerance. Subsequent review of the process used to transfer the alignment from the surrogate to flight UVIS detector revealed an error in the use of a CAD model at Ball. Alternative methods were used for the IR alignment transfer, but the process relied on much earlier metrology of the MUX detector that could not be independently verified.

Additional checks of the UVIS-1 alignment were made at the start of the ambient calibration campaign of June 2004, while the fully-integrated instrument was mounted in the RIAF in the CASTLE stimulus in the SSDIF cleanroom. While the data showed reasonable general agreement with the earlier (Dec-Jan) measurements obtained before the instrument was fully integrated, the tilt of the detector about its X-axis was seen to be discrepant by more than twice the expected measurement error. Furthermore, the variation in Θ_x over three successive measurements was similar in magnitude to the discrepancy (~0.3 degrees), and greater than the adopted alignment tolerance (0.2 degrees). Subsequent attempts to determine the cause of the variation were unsuccessful, although it was clear that turbulence, likely induced by the WFC3 electronics heating air rising through the CASTLE optical path, was degrading the encircled energy determinations that define the focus curves at each field point. This was partially mitigated with longer (10s) exposures, over which the turbulence is averaged.

Thus, the thermal vacuum test program began with a UVIS detector known to be mis-aligned and demonstrating apparent alignment variability of unknown origin, and an IR detector for which the alignment state was unknown.

Measurement chronology

The TV1 program commenced with the WFC3 installed in the RIAF in CASTLE in the SES thermal-vacuum chamber at GSFC, in a configuration similar to that used for the June-July ambient testing in the SSDIF, but with thermal shrouds surrounding the RIAF and instrument. Because complete optical metrology of the apparatus could not be performed due to restricted space in the SES chamber, the CASTLE image position and chief ray direction were aligned to the UVIS channel of WFC3 (by adjusting the two CASTLE fold flats), so that the image location and coma content were the same as in the July ambient measurements (for which the CASTLE alignment was independently set, to best simulate the OTA beam relative to the instrument latches). This resulted in definition of a new ‘M’ series of CASTLE pointings to the standard 16 image positions covering the field of each channel (Hartig, 2003). A full set of 3 consecutive iterations of the alignment measurement SMSs UVAL1S4A, 5A, and 6A were then executed from 28-30 August 2004 (ref. log 2004241c-242d, exposure entries 9526-10293). These SMSs obtain, for each of the (16) field points, monochromatic point source images at 16 different focus settings of the CASTLE, including 9 settings closely spaced about the nominal focus, and 7 additional settings far from focus, including positions near the ends of the CASTLE focus stage travel range. The latter are used for phase retrieval analysis, while the former are used to determine the optimal focus using encircled energy analysis. The parabolic fits to the EE vs. focus position at the 16 field points are then fit to obtain the optimal detector alignment offset in tip/tilt and focus; likewise, a plane was fit to the phase retrieval focus term results. The image locations are compared to their nominal values to determine the detector X and Y offsets and roll angle. As seen in Table 1, the results were reasonably consistent, but again the Θ_x component of detector tilt had changed, by about 0.2 degrees from the July 2004 measurements.

Table 1. Pre-TV1 Ambient UVIS-1 Alignment Test Results

	28-29 Aug 04 -70C "M" a		29-Aug-04 -70C "M" b		30-Aug-04 -70C "M" c	
	EE	PR	EE	PR	EE	PR
Θ_X (^{o})	0.81	0.77	0.91	0.91	0.91	0.84
Θ_y (^{o})	0.07	0.15	-0.05	0.11	-0.03	0.19
Z (mm)	0.744	0.769	0.771	0.782	0.782	0.837
X(mm)	-1.216		-1.203		-1.198	
Y(mm)	0.385		0.419		0.431	
Θ_z (^{o})	-0.355		-0.325		-0.328	

Mean 28-30 Aug 04	
EE only	
Θ_X (^{o})	0.877
Θ_y (^{o})	-0.003
Z (mm)	0.766
X(mm)	-1.206
Y(mm)	0.412
Θ_z (^{o})	-0.336

After an initial pumpdown attempt was aborted due to poor conductance out of the WFC3, while some thermal blanketing was being removed to improve pumping speed, an inadvertent bump of the CASTLE structure occurred. This required adjustment to the CASTLE alignment, on 5 Sept, resulting in the 'N' series of pointings. The SES chamber pumpdown was then successfully executed and vacuum alignment measurements were obtained on 13 and 14 Sept (log 2004256a-258a, entries 10900-11155, 11597-11852), with the instrument in the "hot operate" environment and the detector temperature set to –83 C. The image data quality was found to be excellent, with noticeable improvement over the ambient data attributed to a lack of turbulence in vacuum and solid thermal control of the optical bench and stimulus. Two iterations of the 3 UVAL1 SMSs produced essentially identical results, as displayed in Table 2.

Table 2. TV1 UVIS-1 Alignment Test Results

	13-Sep-04 -83C "N" b		14-Sep-04 -83C "N" c		25-Sep-04 -83C "N" d		3-Oct-04 -83C "N" e	
	EE	PR	EE	PR	EE	PR	EE	PR
Θ_X (^{o})	0.68	0.59	0.71	0.62	0.71	0.65	0.71	0.65
Θ_y (^{o})	0.04	0.20	0.05	0.18	0.03	0.19	0.03	0.16
Z (mm)	0.424	0.453	0.422	0.454	0.369	0.406	0.413	0.443
X(mm)	-1.148		-1.150		-1.015		-0.931	
Y(mm)	0.484		0.485		0.644		0.614	
Θ_z (^{o})	-0.310		-0.312		-0.313		-0.312	

Mean TV#1	
EE only	
Θ_X (^{o})	0.703
Θ_y (^{o})	0.039
Z (mm)	0.407
X(mm)	-1.061
Y(mm)	0.557
Θ_z (^{o})	-0.312

With the instrument in the "hot operate" environment and the detector temperature set at –123 C, the initial evaluation of the IR channel image location and quality was obtained on 11 Sep (log 2004255a, entries 10806-10821). After some confusion regarding the image orientation was corrected with processing software modifications, the images showed clear decenter and defocus, each of about 0.5 mm. The IR corrector was adjusted in both focus and tip/tilt (cylinder rotation) to remove significant defocus and coma. Although a small amount of coma was present in the initial images, for which the corrector was set at the positions that optimized the IR surrogate detector (MUX) images in Dec 2003, a relatively large amount of coma was induced by the required ~ 0.5 mm corrector focus adjustment. This results from the compact optical design, which generates significant pupil shear at the RCP as the focus drive is adjusted.

Following image optimization, the alignment evaluation SMSs IRAL1S4, 5 and 6 were executed successfully on 14 Sep (log 2004256a, entries 11245-11500). Analysis of the phase retrieval data indicated that some residual coma was present (when averaged over the 16 measured field points) as well as a small defocus, so additional corrector adjustments were executed prior to two more iterations of the IRAL1 SMS series (entries 11896-12151, 12219-12474). As shown in Table 3., the IR detector was found to be significantly misaligned in all axes except theta-Z (roll), implying a further problem in the transfer of the alignment from the IR surrogate detector.

Table 3. TV1 IR-2 Alignment Test Results

	14-Sep-04 -123C "N" a		15-Sep-04 -123C "N" b		16-Sep-04 -123C "N" c		24-Sep-04 -123C "N" d		4-Oct-04 -123C "N" e	
	EE	PR	EE	PR	EE	PR	EE	PR	EE	PR
Θ_X (°)	0.71	1.02	0.87	1.12	0.83	1.13	0.78	1.15	0.82	1.14
Θ_y (°)	0.10	0.26	0.29	0.36	0.30	0.34	0.21	0.33	0.31	0.33
Z (mm)	-0.498	-0.548	-0.558	-0.600	-0.556	-0.599	-0.575	-0.622	-0.571	-0.626
X(mm)	0.553		0.829		0.833		0.888		0.870	
Y(mm)	-0.269		-0.522		-0.527		-0.561		-0.561	
Θ_z (°)	0.085		0.086		0.088		0.088		0.084	

Additional iterations of the alignment SMSs for both UVIS and IR channels were executed with the instrument in the “cold operate” environment, on 24-25 Sep (entries 14348-14603) and again on 3-4 Oct (entries 16779-17065). These showed excellent repeatability, and indicate that both channels demonstrate little alignment sensitivity to the instrument thermal environment.

One additional measurement of the IR channel was performed on 5 Oct (entries 17096-17361), with the IR corrector returned to its nominal (center of travel, LVDT set to 2244) focus position, and coma removed with adjustments of +48 and +15 steps on the inner and outer cylinders, respectively. The CASTLE focus positions were offset by +2.75 mm to compensate the detector defocus, so the encircled energy measurements remained approximately centered on the position of best focus. As expected, these data indicate a somewhat different optimal detector alignment (especially in the X position), when the corrector is at its nominal position. The focus (Z) position from the EE measurements must be corrected by the effect of the CASTLE offset (since the focus determination is relative to the center position of the focus scan); this correction amounts to -0.696 mm at the detector, and has been applied to the raw result in Table 4.

Table 4. TV1 IR-2 Alignment Test Results with Nominal Corrector Settings

	5-Oct-04 -123C "N" f	
	EE	PR
Θ_X (°)	0.81	1.18
Θ_y (°)	0.07	0.07
Z (mm)	-.601	-0.650
X(mm)	0.545	
Y(mm)	-0.433	
Θ_z (°)	0.086	

After the thermal vacuum test program completed, the WFC3 was warmed and the SES chamber was vented to ambient. A follow-up set of three iterations of the UVIS alignment SMSs was run on 18-19 Oct (log 2004292a, entries 22467-23234), with detector temperature set to –70 C. These measurements, which were internally consistent, showed a marked change in the Θ_X alignment of the UVIS detector, which increased by 0.45 degrees from the thermal-vacuum measurements, as seen in Table 5.

Table 5. Post-TV1 Ambient UVIS-1 Alignment Test Results

	18-Oct-04 -70C "O" a		19-Oct-04 -70C "O" b		19-Oct-04 -70C "O" c	
	EE	PR	EE	PR	EE	PR
Θ_X (°)	1.12	0.93	1.16	1.13	1.15	1.07
Θ_y (°)	0.00	0.08	0.01	0.14	0.09	0.15
Z (mm)	0.697	0.697	0.736	0.770	0.701	0.772
X(mm)	-1.092		-1.057		-1.064	
Y(mm)	0.431		0.438		0.418	
Θ_z (°)	-0.298		-0.303		-0.302	

	Mean 18-19 Oct 04
	EE only
Θ_X (°)	1.143
Θ_y (°)	0.033
Z (mm)	0.711
X(mm)	-1.071
Y(mm)	0.429
Θ_z (°)	-0.301

Discussion

Prior to installation of the flight detectors a set of alignment tolerances in all 6 degrees of freedom were adopted, as displayed in Table 6. The rationale for the X and Y position range is to maintain the UVIS FOV near nominal and well away from the baffle edges, to avoid potential vignetting. Very minor vignetting is present in the nominal design at the -V3 corner, due to the POM; this also drives the Θ_Z tolerance. It is also desirable to maintain approximate concentricity of the UVIS and (smaller) IR FOV. The acceptable focus (Z) range is set by the desire to use less than 10% of the available focus compensation of the corrector mechanism in the UVIS channel (the remainder reserved for on-orbit adjustment for installation offsets). For the IR channel, the large induced pupil shear that results from corrector focus adjustment argues for a more restrictive allocation, as the requisite corrective cylinder rotations are large and move into uncalibrated regions when focus corrections of >0.5 mm are required. The tip/tilt (Θ_x, Θ_y) budget is derived from a desire for uniformity of focus over the field, which is intrinsically curved and is subject to continuous drift due to OTA "breathing". The larger pixels, greater Airy disc diameter, and smaller physical extent of the IR detector require a somewhat looser tip/tilt tolerance than that for the UVIS detector despite the slower focal ratio of the latter.

Table 6. Adopted WFC3 Detector Alignment Tolerances

	UVIS	IR
X,Y (px)	±20	±10
Z (mm)	±0.85	±0.2
Θ_x, Θ_y (°)	±0.2	±0.3
Θ_z (°)	±0.5	±1.0

The thermal-vacuum measurements have shown that both flight detectors are out of tolerance in their alignment in all but Θ_y and Θ_z. The excellent repeatability of the TV measurements indicates that (non-systematic) measurement errors are much smaller than the tolerances, so the misalignment is significant and must be corrected. There are clear systematic differences in the focus and tip/tilt determinations made with the EE and phase retrieval methods. This is to be expected, since different criteria are used to assess the focus at each field point. While the EE technique optimizes the energy in a small (~3 px) diameter, the PR method fits to the diffraction focus. Both techniques yield out-of-tolerance results of similar magnitude and direction and follow the same global trends over field and from measurement to measurement. We adopt the EE values as most representative of the science performance requirement.

The most puzzling aspect of the UVIS alignment measurements has been the relative variation seen in determinations of the detector tip (Θ_x), accompanied by little movement in image location. The variation is apparent in both the EE and the phase retrieval results, which represent both independent data sets and different analysis techniques. This would seem to implicate an actual rotation of the detector, since most other scenarios that could tilt the focal surface would produce significant changes in image location that is not observed. Yet it is difficult to accept that the focal plane is truly rotating by as much as 1/2 degree if the detector mounts are nominal; the forces required to move the (very stiff) flexures by this amount are huge. It is possible, though unlikely, that one of the mounting interfaces is compromised (a loose insert in the bench or bottomed-out screw are possibilities); these must be carefully examined when the instrument is disassembled following its post-TV evaluation program in the SSDIF. It is also possible that the CCD is subject to rotation with respect to the detector base when the TEC stack under it is thermally cycled. This hypothesis led to direct measurements of the ACS WFC spare (of very similar design) and the WFC3 UVIS-2 detectors at Ball shortly after the Θ_x instability was first discovered in late 2003; both showed very little CCD tip/tilt as their

TECs were cycled, measured in the 10 arcsec range. Nevertheless, this could be a pathological case, perhaps “workmanship” related, so the UVIS-1 detector should undergo similar testing when returned to Ball for re-alignment.

Conclusion

Both UVIS and IR flight detectors were found to be out of tolerance in their alignment with the optical assembly, indicating errors in the transfer of surrogate alignment information to the flight articles. These alignment transfer errors are only partially understood and must be further studied to prevent similar future misalignments, especially for the IR detector, which can only be evaluated in a thermal vacuum environment.

Measurements made at various times through the thermal vacuum test, with the instrument in different thermal environments, demonstrate little variation, indicating good optical bench stability in on-orbit conditions. The small changes in detector centering and focus are most likely due predominantly to variations in the CASTLE stimulus or its interface with the WFC3 (RIAF).

Our best estimate of the offsets required to correctly align the UVIS-1 detector in on-orbit conditions is the mean of the TV results shown in Table 2. These should be directly applied to the UVIS-1 detector using relative 3-space and angular adjustments to the detector interface with its interchange ring, monitoring the changes using the detector alignment fiducials. These values should also be applied, in a relative sense, to the UVIS-2 flight detector before its alignment is tested in the flight instrument, as planned for spring 2005, before disassembly.

While the UVIS-1 detector is at Ball for realignment, further testing to understand the cause of the theta-X instability may be performed, if no strong conclusions regarding its origin have yet been reached. One such test is the monitoring of the focal plane tip/tilt using direct autoreflection with a theodolite during thermal cycling of the CCD.

The Table 4 alignment offset values represent our best estimate of the corrections required to properly align the IR-2 detector; these should be applied, relative to the current IR-2 alignment, to future detector builds. An effort should be made to determine the root causes of the failure of the alignment transfer process from the surrogate (MUX) detector to IR-2 that resulted in these significant offsets, so that future transfers will not suffer similar inaccuracies.

Reference

Hartig, G. “Image Positions for WFC3 testing with CASTLE”, STScI Internal Memo, 15 May 2003.