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THE ON-ORBIT PERFORMANCE OF WFPC2[1]

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ABSTRACT

The second Wide Field and Planetary Camera (WFPC2) was successfully installed in the *Hubble Space Telescope* during the STS-61 servicing mission in 1993 December. The primary objective of this new camera is to provide diffraction-limited photometric imaging over a wide field and a spectral range from 0.12 to 1.0 μm. Here we provide an overview of the characteristics of the new instrument and offer our perspectives based on the first 6 months of operations on-orbit.

Subject headings: instrumentation: miscellaneous — methods: observational — space vehicles

1. INTRODUCTION

In orbit above Earth's atmosphere, the combination of the WFPC2 and the *Hubble Space Telescope* provide significant advantages in observations of crowded and complex fields, access to familiar detail in more distant objects, high contrast across small spatial scales, a large field of view compared to expectations for ground-based adaptive optical systems at visible wavelengths, and high-resolution imaging at UV wavelengths shortward of Earth's atmospheric cutoff. With the commencement of Cycle 4 observations early this year, the *HST* General Observer community has begun using the WFPC2 to address a diverse range of astronomical programs.

WFPC2 incorporates internal optical corrections for the abberated *Hubble* primary mirror, as well as new developments in CCD sensors, signal chain electronics, optical filters, UV performance, and measures have been taken to improve the calibration of the instrument and operational efficiency. In brief, the WFPC2 specifications call for a scientifically capable camera configured for continuous operation in space with a minimum of maintenance and operational overhead. The WFPC2 retains a strong engineering heritage from the original WF/PC, addresses essentially the same quantitative science goals (Trauger et al. 1992), and facilitates the science programs once intended for the WF/PC in earlier proposal cycles (Westphal et al. 1982).

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Instrument calibrations are an ongoing activity. Our first knowledge of the integrated instrument from system-level thermal-vacuum tests (TVT) at JPL in 1993 April–May and was reported in a WFPC2 Science Calibration Report submitted to NASA and the STScI in 1993 November by the WFPC2 science team (Trauger et al. 1993). The detailed analysis of early WFPC2 on-orbit calibrations will appear in a number of forthcoming reports: an early summary of WFPC2 status (Holtzman et al. 1994), a revision of the detailed 1993 November report, and additional papers on WFPC2 photometry, image quality, and CCD performance. The instrument characteristics as known in 1994 March are detailed for the General Observer in the WFPC2 Instrument Handbook (Burrows et al. 1994).

2. OPTICAL SYSTEM

The WFPC2 field of view is divided into four contiguous subfields by a pyramid mirror near the *HST* focal plane, and these four subfields are imaged by separate cassegrain relay cameras and CCD sensors. The strategy for correction of the *Hubble* aberration preserves the basic optical configuration of WF/PC, but with a corrective figure added to the relay secondary mirrors and substantially tighter requirements for optical alignment. Demands of budget and schedule forced a reduction in scope of the WFPC2 instrument in 1991 August, resulting in a reduction in number of relay cameras and CCDs. There are four sets of relay optics and CCD sensors in WFPC2, rather than the eight in the original WF/PC. Three of these relay cameras provide well-corrected imaging with a focal ratio of f/12.9 (WFC), and the fourth is well corrected at f/28.3 (PC). The pyramid mirror rotation mechanism has been eliminated, and the four cameras are now permanently aimed at contiguous fields of view. The cameras are denoted PC1, WFC2, WFC3, and WFC4. Four articulated mirror mounts have been added to allow fine alignment of the optics on-orbit.

A number of independent analyses in late 1990 and early 1991 provided an accurate prescription for the WFPC2 corrective optics, based on our star images obtained with WF/PC and FOC on-orbit and examination of the metrology fixtures used during the final figuring of the *HST* primary mirror (Vaughan 1991). We learned that the surface of the primary mirror was figured to the incorrect conic constant: -1.0139 ± 0.0005 rather than the -1.0023 design specification, resulting in a large amount of spherical aberration. By design, WFPC2 creates images of the *Hubble's* exit pupil (essentially images of the aberrated primary mirror) near the surfaces of its four relay cassegrain secondary mirrors. This design was originally intended to minimize vignetting in the relay optics, but for WFPC2 the superposition of the exit pupil image (complete with its aberrated wavefront) on the relay secondaries serves an additional purpose. The optical figure of the WFPC2 secondary mirrors have been modified with the addition of a compensating "error" in conic constant.

Strict new requirements on optical alignment were created by the steep corrective figure on the secondary mirrors. With the corrective prescription for spherical aberration polished into the relay assemblies, small optical misalignments reveal themselves as coma in star images and can be eliminated with pickoff and fold mirror adjustments. Four new mechanisms were introduced in WFPC2 to provide fine alignment as required on-orbit. The 47° pickoff mirror was given $\pm 0\overset{\circ}{.}25$ tip-tilt capabilities with the addition of a flexure mechanism driven by stepper motors, to compensate for prelaunch uncertainties in the instrument orientation (latch positions) relative to the *Hubble* optical axis. Such uncertainties would be insignificant in an unaberrated telescope, but are critical in the corrective optical system. In addition, three of the four optical trains (in the PC1, WFC3, and WFC4) include internal fold mirror mechanisms, with tip-tilt motions up to $\pm 0\overset{\circ}{.}06$ provided by innovative electrostrictive ceramic actuators within invar flexure mountings. The pickoff and fold mirror mechanisms assure accurate superposition of the exit pupil images and the corrective optics by providing adjustment ranges up to $\pm 21\%$ and $\pm 4.8\%$ of the pupil diameters, respectively.

2.1. *On-Orbit Adjustments*

Pickoff mirror adjustments were made in 1993 December based on star images taken with a raster of pickoff mirror positions, for a final correction of 1.6% of the pupil diameter from the launch position. Final adjustments of the three fold mirrors was completed on the basis of phase retrieval analysis of star images at 0.502 and 0.953 μm taken as far as ± 40 mm from nominal *HST* focus in 1994 March, with the final pupils offset from their prelaunch positions by 0.49%, 0.72%, and 0.18% pupil diameters in the PC1, WFPC3, and WFC4, respectively. Less than 15% of the available tip/tilt ranges were required, confirming the accuracy of our knowledge of the telescope metrology, the success of the prelaunch instrument alignment, and the structural integrity of the instrument.

The optical wavefront quality of the WFPC2 and *HST* in operation together was determined from the far-from-focus images in terms of Zernike polynomials. Exclusive of focus and coma terms, the residual wavefront errors were 0.029, 0.029, 0.034, and 0.037 μm rms. Following on-orbit optical alignment, the magnitude of coma is comparable to measurement errors of ~ 0.005 μm rms. As measured in system level tests and confirmed on-orbit, the dominant wavefront errors in WFPC2 are the discrepancies between focus positions in the four individual relay assemblies, equivalent to -0.032, 0.009, 0.032, and 0.016 μm rms, respectively, relative to the midpoint of all four in the f/24 beam. The WFPC2 contains no internal focus mechanism, and instead depends on the *HST* focus which has been positioned for the best imaging in the PC1. *HST* focus varies in response to solar illumination on its external structure by as much as ± 0.4 mm (± 0.011 μm) in a 96 minute orbit. The current focus choice with WFPC2 optimized for the PC1 minimizes sensitivity to *HST* focus shifts in the best-sampled focal plane at the cost of compromising the focus in the WFCs. Due to undersampling in the WFCs, this will have little impact on science observations.

3. FOCAL PLANE AND CCD CHARACTERISTICS

The characteristics of the CCD sensors are central to the fidelity of the conversion of images formed by *HST* and WFPC2 optics to digital signals. The CCDs for WFPC2 were newly manufactured by Loral in 1991, then processed and packaged for flight at JPL. These differ significantly from WF/PC devices built by TEXAS Instruments in 1980. The WF/PC pixel format (800^2, 15×15 μm pixels) has been preserved in the WFPC2 CCDs in order to maintain compatibility with the existing WF/PC data interface. The new CCDs are superior to the WF/PC devices in many areas important for a well-calibrated instrument on-orbit. The absolute quantum efficiency (QE) is lower at visible wavelengths, however, as a consequence of frontside illumination, since the incident light must pass through a polysilicon gate structure overlying the ~ 10 μm thick active silicon layer. The CCD QEs are stable over time, do not require massive UV flooding or other external influences for QE maintenance, and the QE is accurately repeatable following thermal cycles. Laboratory tests find no evidence for QE hysteresis, which would manifest itself as QE variations on timescales of seconds to hours in response to previous exposure history. Linear capacity (full-well) for these devices is $\sim 70{,}000$ electrons pixel^{-1}. The excess charge in deep overexposures is conserved and contained ("bloomed") within the CCD column of origin. The CCDs recover quickly from deep overexposures (100 times full-well or more), showing no measurable residual images in long dark exposures a half hour after the overexposure. The front surface is overcoated with a stable lumogen phosphor ($C_{22}H_{16}N_2O_2$), which serves as the primary detection medium for photons shortward of ~ 0.48 μm, converting these to 0.51–0.58 μm for detection by the CCD.

The system read noise is ~ 5 electrons rms pixel^{-1}. Two independent signal chains provide 12 bit digitization of the CCD charge, with a choice of digitization ratios of either 7 or 14 electrons/DN. The analog-to-digital converter (ADC) errors present in WF/PC have been mostly eliminated by a timing adjustment, but the ADCs still have a systematic tendency to underestimate the signal by a fraction of one DN. A table of average ADC offsets versus DN is available for use in data reductions.

3.1. *Sampling of the Focal Plane*

The WFPC2 pixel scales are $0\overset{''}{.}0455$ and $0\overset{''}{.}0966$ pixel^{-1} at the centers of the PC and WFC fields of view, respectively. Since 65% or more of a star's energy falls within a $0\overset{''}{.}1$ radius at visible wavelengths, star images are spatially undersampled in the WFCs and to a lesser degree in the PC as well. In addition, the physical boundaries between pixels are intrinsically "soft" due to the details of structure and the charge collection process within the CCD. This effectively reduces pixel-to-pixel contrast and MTF, an effect which is seen in both backside and front-side illuminated CCDs (Jorden, Deltorn, & Oates 1994), and has been measured in both WFPC2 TVT data and laboratory work with CCDs identical to the WFPC2 devices. The combination of spatial undersampling and the CCD MTF effects affects the limiting sensitivities of the WFPC2 cameras and must be considered in the photometry procedures. For example, with pixel dimensions comparable to the radius of star images, a star centered within a pixel produces a larger peak signal than the same star positioned at a pixel corner. On the other hand, the MTF effect works to reduce the difference between these two extreme cases. The irregularities due to random subpixel positioning of star images can be mitigated somewhat by obtaining image pairs offset by $n + 0.5$ pixels, where n is a small integer. All things considered, the limiting V magnitudes for WFPC2 are ~ 27.5 and 28 in the PC and WFCs, respectively, for S/N of 5 in a 2000 s exposure.

3.2. *On-Orbit Environment and CCD Operational Adjustments*

The charged particle environment at *HST*'s orbit creates a number of CCD calibration problems not experienced on the ground, including the immediate effects of proton and cosmic-ray ionization tracks, generation of CCD pixels with increased dark rates (hot pixels), and in the longer term (years) charged particle displacement damage which affects charge transfer efficiency (CTE) and bias levels (Hopkinson 1994). In addition, the outgassing of molecular vapor contaminants from structures and mechanisms in the focal plane area of the *HST* was a critical factor not well known prior to the servicing mission. These factors are all affected by the CCD operating temperature. On-orbit measurements of hot pixels, parallel CTE, and the accumulation rate of FUV absorbing molecular condensates on the cold CCD windows suggested that an operating temperature of $-88°$ C would provide a better engineering balance between these competing effects than the original setting of $-78°$ C. The setpoint was therefore changed to $-88°$ C in 1994 April, and will be the nominal operating mode for the foreseeable future.

The effects of protons and cosmic rays are similar to those in the WF/PC experience (WF/PC Investigation Definition Team 1991). In WFPC2, ~ 100 cosmic-ray tracks are detected per minute outside of the SAA, affecting ~ 700 pixels. Hence 0.1% of all pixels are affected even in the shortest possible exposure time. Nearly 4% of all pixels will be affected in a 2000 s exposure. The standard corrective measure is to "CR split" long exposures into two or more.

Energetic particles also generate new pixels with dark currents statistically significant above the nominal background rates, defined as hot pixels. The WFPC2 CCDs arrived on-orbit in 1993 December with uniform dark rates of ~ 0.013 electrons pixel^{-1} s^{-1} at $-78°$ C and immediately began developing a new population of hot pixels. These hot pixels partially anneal during the exposure to temperatures of 22° C during the monthly CCD maintenance warmup cycles, but do not completely reset to the original background dark rate. The number of pixels per CCD n with dark rates greater than r electrons pixel^{-1} s^{-1} can be approximated by the power law: $n = n_0 \times (r/r_0)^{-\gamma}$, for $r > r_0$ with $\gamma \approx 1$. Following the change to $-88°$ C CCD operation in 1994 April, n_0 amounted to ~ 400 pixels with rates $r_0 \approx 0.02$ electrons pixel^{-1} s^{-1} or more. New hot pixel generation leads to an increase in n_0 of ~ 24 pixels day^{-1}. The effect of monthly CCD warmup cycles on-orbit ($\sim$6–12 hr at 22° C) is to reset most of these to levels below 0.02 electrons pixel^{-1} s^{-1}. The background dark rates for unaffected pixels is ~ 0.003 electrons pixel^{-1} s^{-1} at $-88°$ C. The standard corrective measure is to use up-to-date dark exposures for mapping and subtraction of the excess signal in hot pixels during analysis. Frequent updates of the CCD hot pixel maps are required for data calibration. Currently, long (1800 s) dark exposures taken ~ 20 times per month.

A parallel CTE problem was identified in photometry of a star field with multiple pointings, manifesting itself as a difference in apparent star brightness as a function of CCD row number. The photometry of individual stars varied as much as 4% between rows 1 and 800 on a given CCD in $-88°$ operation. This has been investigated both in WFPC2 calibration observations on-orbit and in laboratory experiments with identical CCDs. It is caused by electron traps in the CCD silicon, numbering a few per pixel, each capable of trapping a single electron with a binding energy of a fraction of an electron volt. Charge is removed from the image during the CCD readout in a manner that is dependent on both star brightness and sky background levels. It is seen most clearly in images of bright stars in a dark field, but is not seen in fields of faint stars against a comparably bright background, nor is it seen in flat-field images. A simple corrective algorithm based on our knowledge of single-electron traps has been devised and validated against ω Cen starfield photometry and laboratory simulation data. The accuracy of the correction should be no worse than $\sim 1\%$ in $-88°$ C data. As a standard corrective measure, the CTE corrective algorithm can be used to estimate the importance of scene-dependent CTE effects in a given image, and then used to make the corrections only if required.

4. PHOTOMETRY

Our design goals for photometric accuracy are 1% in all filters, which implies that the relative response in all 800^2 pixels per CCD be known to comparable precision in flat-field images taken through each of the 48 filters. Success in this area is dependent on detailed knowledge of CCD characteristics, signal chain, filters, and optical performance. The on-orbit calibration program is fundamental to the accuracy of WFPC2 photometry, and the user is advised to seek the latest information from the instrument databases maintained by the STScI.

Revisions have been made to the set of 48 optical filters, based on considerations of the effectiveness of the WF/PC filter set in science programs, and as defined in a number of science workshops and technical reviews. The filter set provides continuity with the WF/PC "*UBVRI*" in the F336W, F439W, F555W, F675W, and F814W sequence. Calibration of these filters against WF/PC and Johnson Cousins photometric systems is in progress. The "Wide *UBVRI*" WF/PC photometric filters are included and extended into the far-UV. An experimental "Wood's filter" has been added to the far-UV filter complement, using the optical properties of a thin metallic sodium film to provide a broad solar-blind UV passband (0.12–0.21 μm) with strong suppression (10^{-8} or more) of longer wavelengths. Narrowband filters were manufactured for stable and accurately uniform spectral profiles over the filter clear apertures. The narrowband set now includes a linear variable filter which provides a passband FWHM $\delta\lambda/\lambda \approx 1\%$ over a 0.37–0.98 μm wavelength range. Strömgren *uvby* filters have also been added.

WFPC2 sensitivities have been measured in photometry of ω Cen cluster stars and a number of UV flux standard stars. The updated sensitivities have been incorporated in the photometry tables in Version 2.0 of the WFPC2 Users Handbook, but calibration activities are ongoing. Sensitivities shortward of 0.3 μm are lower than predictions published in Version 1.0

of WFPC2 Users Handbook, which went to press prior to the WFPC2 system level tests in 1993 April–May. They are generally consistent with expectations following analysis of TVT data.

The intrinsic CCD response is uniform within a few percent, with the exception of a manufacturing pattern defect which generates a $\sim 3\%$ reduction in QE in one out of every 34 rows. This pattern defect is identical in all CCDs. Initial pipeline flatfields were derived for all WFPC2 filters by combining high spatial frequency (pixel-to-pixel) QE maps from TVT data, and the low and mid spatial frequency components (due to vignetting variations over the field of view) from TVT data adjusted with models of the OTA. The high spatial frequency flat-field component seen in on-orbit data is within 0.5% of that seen during the TVT. The low and mid spatial frequency flat field components are essentially wavelength-independent and have been derived from on-orbit Earth-pointing images (Earth flats) in four narrowband filters. The STScI calibration database was updated on the longward of 0.3 μm are believed accurate to $\sim 1\%$. Flat fields shortward of 0.3 μm cannot be verified directly, since far-UV Earth flats are significantly affected by residual filter throughput longward of 0.3 μm. The flat-field data are unaffected by the parallel CTE problem discussed in § 4. The evident repeatability of the high-frequency flat field features and the stability of the optical alignment demonstrate that the WFPC2 flat fields are "calibratable" to within 1%. Further minor refinements will undoubtedly be made following further analysis and experience on-orbit. The instrument throughput shortward of 0.2 μm is extremely sensitive to molecular vapor condensation on the cold field flattener window of the CCD package. Contamination rates in January at the $-78°$ C setpoint caused a decrease in throughput at 0.17 μm at a rate of $\sim 10\%$ per month. This initial rate decreased to a few percent per month at 0.17 μm after 3 months of operation. The new $-88°$ C setpoint caused the contamination rate to increase 10 fold in April, to an initial rate of $\sim 20\%$ per month. In all cases, the monthly CCD thermal cycles accurately reset the far-UV throughput to the initial (1993 December) conditions, indicating that the all molecular contamination experienced on-orbit cleans up completely in less than 6 hr at $+22°$ C. Photometry in the far-UV requires knowledge of the contamination state and throughput levels at the time of each observation. This knowledge is provided by periodic observations of UV flux standard stars.

All WFPC2 Servicing Mission Observatory Verification (SMOV) science calibration proposals ran to completion in May, and the longer term Cycle 4 calibrations began. The ongoing cycle 4 calibrations include periodic photometry of star fields (ω Cen and UV flux standard stars), flat-field calibrations (Earth "streak" flats longward of 0.3 μm and star streaks for UV flats), internal monitors (CCD bias frames, internally generated flat-fields), and monitoring of the UV throughput levels with standard star observations. Calibration activities remain an ongoing collaboration between the WFPC2 Investigation Definition Team and the WFPC2 instrument scientists at the STScI.

5. SUMMARY

The WFPC2 has completed its first six months of operation following the Hubble servicing mission in 1993 December. The instrument is in excellent condition and calibration of the instrument is converging as expected. We look forward to a rich harvest of new science observations as the *Hubble* astronomy community makes use of its new facility on-orbit.

The WFPC2 instrument was made possible through the dedicated and skilled efforts of many individuals who carried out the engineering and instrument manufacture at Jet Propulsion Laboratory, project management at the Goddard Space Flight Center, operations planning at the Space Telescope Science Institute, and overall program management at NASA headquarters. Science oversight was provided by the WFPC2 IDT and a number of science advisory working groups.

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