On-orbit performance of the HST Wide Field Camera 3

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ABSTRACT

The Wide Field Camera 3 (WFC3) was installed into the Hubble Space Telescope during Servicing Mission 4 in May 2009. This panchromatic camera considerably improves the ultraviolet, visible, and infrared imaging capabilities of HST. Commissioned over the summer of 2009, WFC3 is now fully functional and responsible for approximately half of the Cycle 17 HST Science Program. This paper will review the scientific performance of WFC3 including its sensitivity in absolute terms and relative to other HST instruments. The paper will also discuss the calibration programs for WFC3 and the achieved photometric and astrometric calibration accuracies. Lessons learned from the ground calibration and in-flight commissioning will also be considered.

Keywords: Hubble Space Telescope, Ultraviolet Imaging, Infrared Imaging, Servicing Mission 4, WFC3

1. INTRODUCTION

The Wide Field Camera 3 (WFC3) is a fourth generation science instrument for the Hubble Space Telescope. Developed by the NASA Goddard Space Flight Center together with the Space Telescope Science Institute, WFC3 is designed to assure that HST has powerful imaging capabilities for the future[1,2]. WFC3 was installed into HST in May 2009 by the crew of STS-125 during Hubble Servicing Mission 4. WFC3 complements and provides redundancy for the HST Advanced Camera for Surveys (ACS) in the 400 to 1000nm wavelength range. It improves upon the ACS performance with a substantially larger set of filters, finer spatial sampling, and new CCDs. In addition, WFC3 greatly improves HST's performance for near Ultraviolet and near Infrared imaging by factors of greater than twenty compared to prior instruments.

WFC3 was designed and developed as a *facility instrument* for HST under the guidance of Science Oversight Committee selected from the international scientific community and chaired by Prof. Robert O'Connell of the University of Virginia. Day to day development was guided by GSFC and STScI scientists and engineers. Our principal industrial partner was Ball Aerospace who provided the most of the optical, electrical, mechanical, and software elements plus significant systems engineering support.

WFC3 replaced the long serving WFPC2 (December 1993-May 2009) camera in the HST radial bay slot during EVA#1. While the servicing mission had a few tense moments when the A-latch bolt retaining WFPC2 in the observatory initially refused to budge, the actual installation of WFC3 went very smoothly. WFC3 passed its initial systems checks during and shortly after EVA#1 and was then left in a safe state for the remained of the servicing mission.

2. INSTRUMENT DESIGN AND CAPABILITIES

WFC3 is a two channel imaging instrument with separate Ultraviolet-Visible (UVIS) and Infrared (IR) channels (see Figure 1). Incoming light from the center of the HST field of view is captured by a pickoff mirror and directed into the instrument using the same design as WF/PC-1 and WFPC2.

For the UVIS channel, where reflection losses are significant in the ultraviolet, the light undergoes only two additional reflections. The M1 mirror (movable in tip-tilt and piston) re-images the HST pupil onto the M2 mirror. The M2 mirror provides the correction for the HST primary mirror's spherical aberration and completes the re-imaging from the f/24 HST to f/31 yielding a plate scale of 39 milli-arcseconds per pixel at the detector. The UVIS detector is a pair of e2v

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Type 43-62 CCD devices with 15 micron pixels. These 4096x2051 pixel detectors are optimized for response in the 200 to 400 nm wavelength region and provide response to ~1000nm. The field of view of the UVIS channel is 162 x 162 arc seconds. This field is limited by the dimensions of the pick-off-mirror and the need to avoid blocking light reaching the other HST instruments. As a consequence, WFC3 has smaller pixels than ACS's Wide Field Channel (40 versus 50 milli-arcseconds). This plate scale better samples the HST point spread function but is still somewhat under-sampled. The UVIS channel contains a "Selectable Optical Filter Assembly" (SOFA) that originally flew in space inside the WF/PC-1 instrument (April 1990 – December 1993). The SOFA consists of individually rotatable wheels each of which carries four filter plus an open slot. This provides 48 filter elements. The WFC3 filter complement consists of 42 full field filters, 5 "quad" filters that provide four passbands each over a limited portion of the field of view, and a ultraviolet grism. Between the SOFA and detector assembly lies a mechanical shutter which closely copies the design of the ACS/WFC shutter.

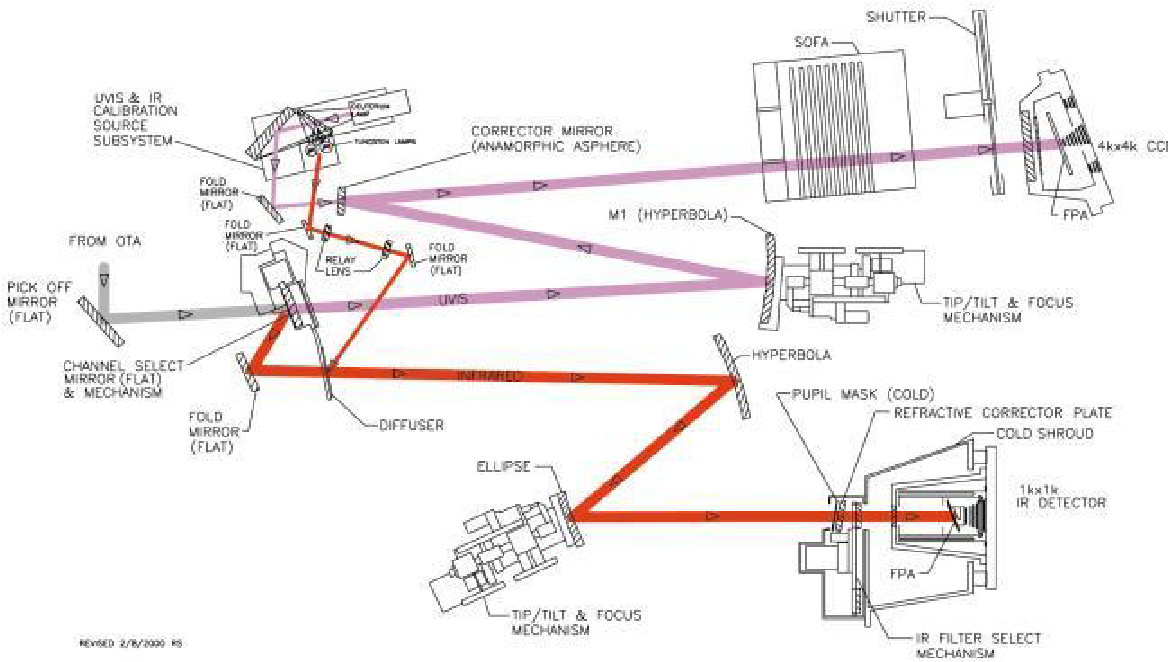

Figure 1. Optical-mechanical schematic for WFC3.

For the IR channel, when reflection losses are minimal due to the use of protected silver mirrors, the incoming light is deflected by inserted the Channel Select Mechanism flat mirror. A fold mirror followed by a M1 + M2 pair of mirrors to re-image the HST f/24 beam to f/11 brings the light to a cooled transmissive "refractive corrector plate"(RCP). This lens provides the correction for the HST spherical aberration and is co-located with a cold stop at the HST pupil. The IR channel has a 1014 x 1014 pixel Teledyne HgCdTe Hawaii-1R focal plane infrared detector. Its 18 micron pixels provide a 123 x 139 arc second field of view with ~130 milli-arcsecond pixels. This significantly under-samples the excellent HST point spread function. However, unlike NICMOS, the intrapixel response of the WFC3 detector is very uniform and good image quality can be achieved via the combination of multiple dithered (slightly displaced) images.

To adequately cool the infrared detector array while minimizing the power demands upon HST, WFC3 uses a 6-stage thermal electric cooler (TEC) in an enclosure cooled to ~-30C using a block of 1-stage TECs (see Figure 2). This cold enclosure also serves to cool the cold stop, RCP, and 18 element filter wheel. In addition, the hot side of the 6-stage TEC is attached via a heat pipe to a second block of 1-stage TECs. All of the 1-stage TECs are mounted on an external radiator that is prohibited from being exposed to direct sunlight by HST operational rules (see Figure 3).

The WFC3 is packaged in the original WF/PC-1 enclosure returned to earth in December 1993 after the first HST servicing mission. This enclosure, and its thermal radiator, was extensively modified for use by WFC3 but retain their original form factor and interfaces to HST (including latches and electrical interfaces). The electronics and flight

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software supporting WFC3 have essentially no commonality with the prior WF/PC-1 and WFPC2 instrument. Instead, they are based strongly on the heritage of the Ball Aerospace developed NICMOS, STIS, ACS, and COS instruments.

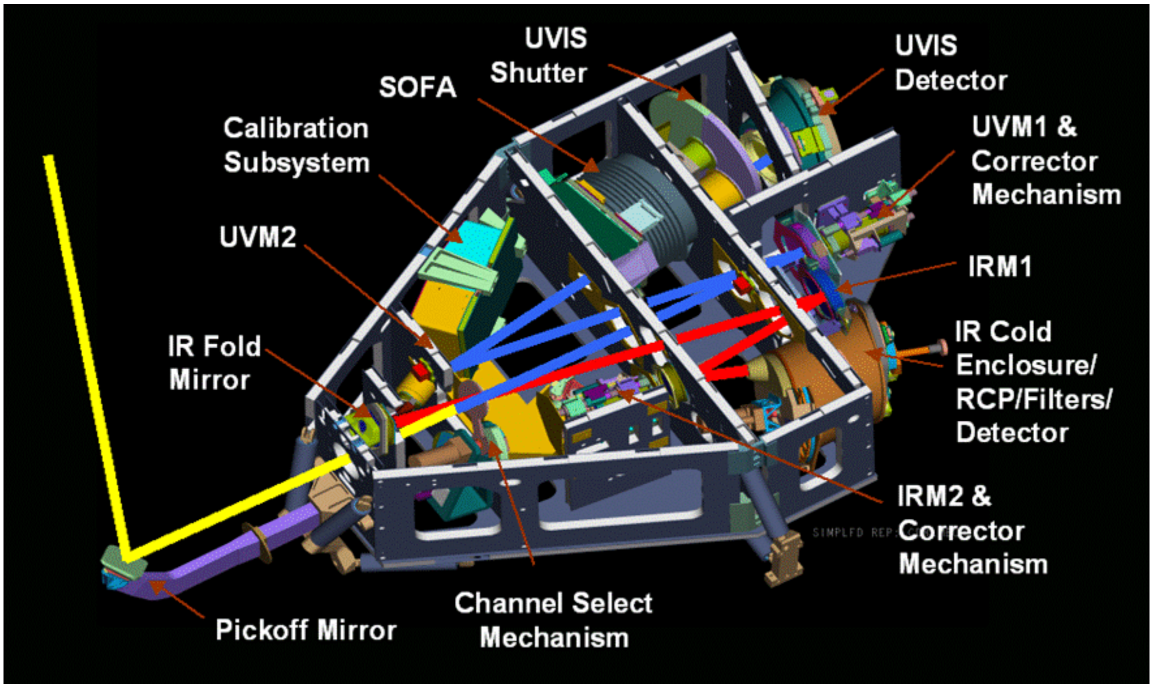

Figure 2. Optical bench and its major components. The yellow line traces the incoming f/24 beam from the HST telescope assembly. The blue line traces the UVIS channel and the red line the IR channel optical paths.

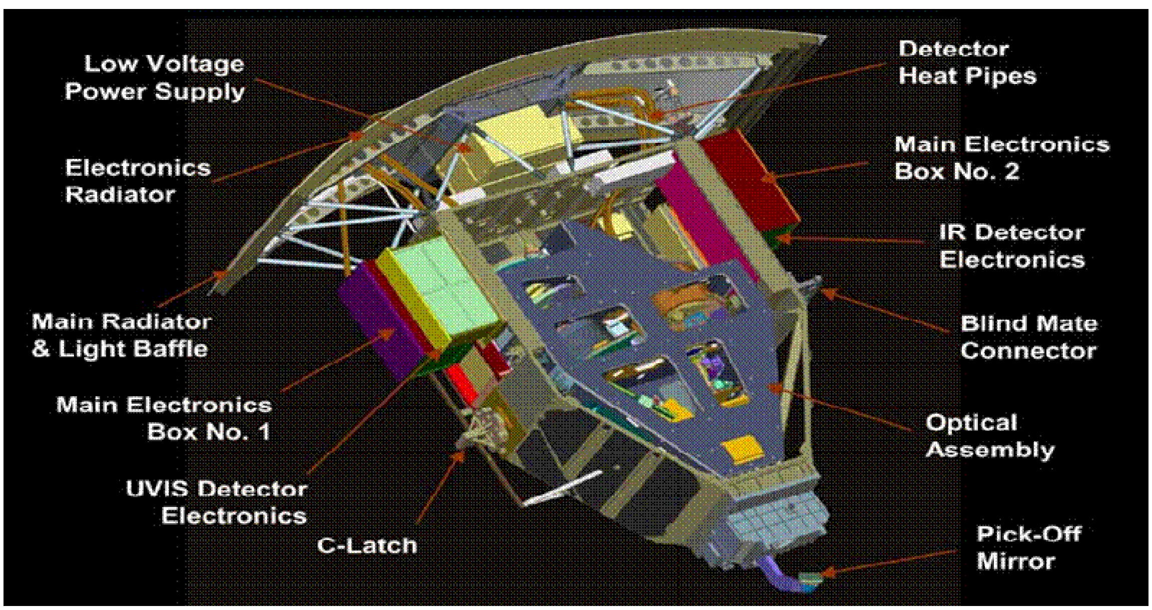

Figure 3. Optical bench located within the WFC3 enclosure. Locations of the radiators, electronics boxes, and some other elements are shown.

3. WFC3 PROJECT HISTORY

The timeline for the development of WFC3 proved to be longer and more complex than initially expected. NASA solicited a new instrument for SM4 in 1997 for a planned mission in mid-2002. This led to the selection of the Cosmic

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Origins Spectrograph (COS). In parallel, a decision was reached to extend the lifetime of HST from a planned 2005 termination to 2010. This mission end date would have resulted in the HST imagers being operated well beyond their design lifetime (ACS at 9 years and WFPC2 at 16). Consequently, an effort was started within the HST Project at GSFC to develop a new imaging using the designs and assets available to the Project. The development of WFC3 with a CCD channel derived from ACS was approved in 1998 (at which time the target launch date was mid-2003). Multiple inputs from the astronomical community, including the "Second Decade Committee", led to the study of the feasibility of adding an infrared capability to WFC3. This was incorporated into the WFC3 design in 1999.

By early 2003, SM4 was anticipating a launch in early 2005 when the Orbiter Columbia and her crew were lost during re-entry. The design and major components of WFC3 were completed by late 2003 and delivered to GSFC for final assembly and test. In January 2004, NASA cancelled SM4 placing the future of WFC3 in considerable doubt. While options were considered, the WFC3 assembly was completed and a limited system level thermal vacuum test (SLTV) was carried out over the summer of 2004. Over 2004-5, the WFC3 design (but not the actual hardware) was modified to support robotic servicing of HST. When SM4 using the Space Shuttle was restored, testing resumed with SLTV#2 and SLTV#3 conducted in 2007 and 2008. WFC3 was delivered to Kennedy Space Center in August 2008 for a planned October 2008 launch. However, the failure of the primary side of the HST's instrument control computer led to an additional delay until May 2009 when STS-125 carried the SM4 crew, WFC3, COS, and a host of other items to refurbish and extend the life of HST successfully into space.

The servicing of HST went extremely well with all objectives accomplished. Following a couple of hours of initial testing of WFC3 to assure that it was basically healthy and its electrical interfaces to HST were functional, WFC3 was placed into a safe state with heaters enabled to avoid condensing any volatiles onto its optical surfaces. Three weeks after HST was released by the Space Shuttle, the WFC3 detectors were cooled to the operating temperatures. The commissioning of the instrument including optical alignment and initial calibration, was conducted over the summer with first science observations in late July and full science operation underway in August.

4. DETECTOR DEVELOPMENT

Two early decisions in the development of WFC3 played a key role in its development and ultimate performance. These were (1) that detector technology was the area most important for additional investment and (2) that the instrument should be designed to permit rapid changeout of its detectors until a few weeks before launch. It is largely self-evident that the performance of detectors is directly related to the performance of an imaging instrument. The WFC3 Project directed considerable effort towards acquiring and characterizing the best possible detectors for this instrument.

4.1 Interchangeable Detectors

There are two compelling reasons to design for rapid detector changeout: as a hedge against late in the flow failure and to permit continuing improvement in the detector performance. To accomplish this, the WFC3 detectors are assembled into sealed packages that incorporate their pre-amplifiers and thermal cooling systems (i.e. TECs). This approach was used for most of the HST detectors in prior instruments. What was new in the WFC3 approach was the requirement that changeout be possible in 24 hours (actually, the as-built instrument would probably require closer to four days of work to replace a detector package). This was accomplished by a careful optical alignment transfer process during the detector package assembly that placed the detector surface in a known relationship to kinematic mounts on the package. Each detector assembly was also fully tested including thermal cycling prior to acceptance. A fully qualified flight plus spare was required for each channel. In actuality, the WFC3 Project completed three UVIS and four IR detector packages whose histories are described in the following sections.

4.2 UVIS CCD Detectors

The WFC3 UVIS Channel uses CCD detectors with a format and packaging design nearly identical to the ACS Wide Field Channel (WFC). A major scientific decision early in the design process was to emphasize the near ultraviolet performance of WFC3 rather than red light as was done by the ACS/WFC. To place this in context, WFPC2 offered a comparable field of view ultraviolet capability but with quite low sensitivity. It had older technology filters which either had significant long wavelength "leaks" or fairly low throughput plus the detector achieved 120nm to 300nm sensitivity by conversion of UV photons using a phosphor. The ACS offered two ultraviolet capable channels: the Solar Blind Channel (SBC) covers the 120 to 200 nm region using a photon counting MAMA detector and the High Resolution Channel (HRC) covered 200 to 1000nm using a UV optimized CCD. However, the SBC and HRC each only have a field

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of view of 25x25 arc seconds. The WFC3 provides a field of view more than 30 times larger than SBC or HRC while covering 200-1000nm. Advances in detector technology give WFC3's UVIS channel lower readout noise (3e- versus 5e- in ACS), higher 200-300nm quantum efficiency, and improved filter throughput and out of band rejection. Thus WFC3 could add a significant scientific capability (wide field sensitive near ultraviolet imaging) while still providing redundancy to ACS/WFC at slightly lower sensitivity at wavelengths longer than 800nm.

The initial procurement of CCD detectors met specifications and the two best devices were installed in the instrument for SLTV#1 in 2004. Unfortunately, problems within the detector packages (loose conductive particles that could result in short circuits and damage to the TEC elements during testing) degraded the flight detector package. Consequently, SLTV#2 in 2007 was performed with a degraded flight spare UVIS detector assembly. Careful work at Ball Aerospace resulted in the replacement of the TEC in the flight CCD package in time for SLTV#3 in 2008 and these CCD devices were flown. A second flight spare CCD package was built and tested in parallel with the repair so that the WFC3 Project retained a viable spare plus the original spare to support testing in SLTV#2 and other ground tests. Throughout this process, the availability of a working detector package was very important to testing and resolving other instrument issues and permitted the team to retain flexibility for various launch schedules.

4.3 IR HgCdTe Detectors

The WFC3 infrared detector was developed specifically for this application. The primary scientific requirement was to fully realize the potential of HST for near infrared observations in sensitivity, angular resolution, and photometric stability while doing this within the cost, power, schedule, and technical limitations of the WFC3 instrument. A succinct statement of this goal was to achieve zodiacal background limited observations over the WFC3 field of view in the J and H bands. The resulting design provides Y,J,H broad band imaging in filters of varying widths, narrow band filters for key spectral features, and full wavelength coverage for slit-less spectroscopy from 0.8 to 1.67 microns.

The primary constraints on the detector development were to meet specification in quantum efficiency, dark current, read noise, bad pixels, device generated glow while operating at ~150 degrees Kelvin. It was also necessary to have a detector and package able to withstand several hundred thermal cycles since continuous power from HST could be requested by not guaranteed. Experience with the NICMOS instrument led to the inclusion of "reference pixels" along the edges of the detector to assure accurate measurement of the reference signal levels. This significantly improves the calibration of the instrument (together with various other improvements to the IR channel detector electronics and its power supplies).

The history of the infrared detector development program is captured in Figure 4. Prior to 2004, the WFC3 project's best detector was FPA #64 (numbering reflects a certain point in the fabrication flow – not that 64 working detectors were delivered from Teledyne). This part was assembled into package IR-2 (IR-1 was recycled from an earlier part and used later for FPA #129) and used in SLTV#1 in 2004.

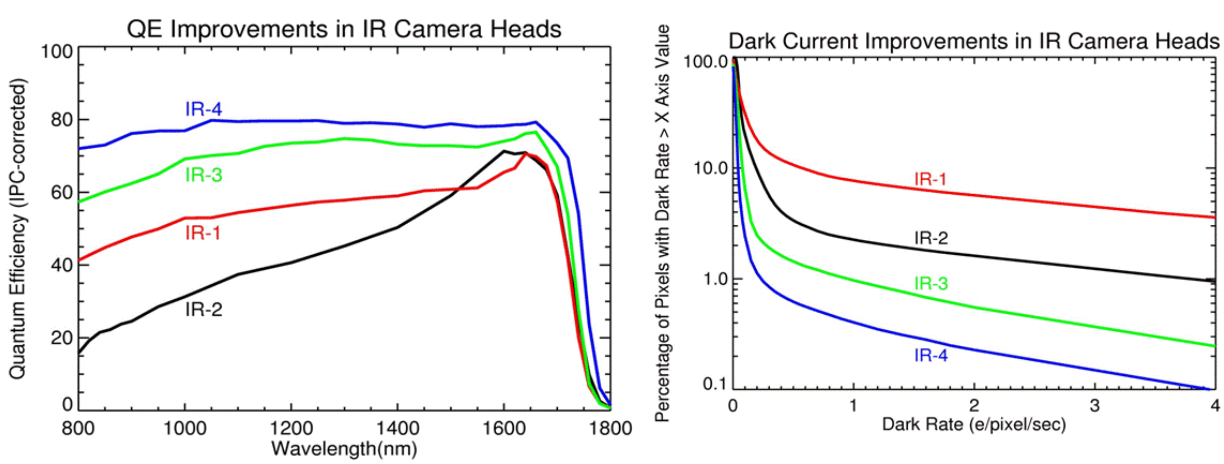

Figure 4. Quantum Efficiency (corrected to inter-pixel capacitance) and Dark Current for the detectors successfully carried to assembled and tested flight detector assemblies.

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Unfortunately (or perhaps fortunately), it was discovered during extensive testing of devices from the same lot as FPA #64 that protons at levels expected in low earth orbit induced glow at levels comparable to or several times greater than the expected zodiacal background. This discovery was made only because the WFC3 team was testing operating detectors and attempting to simulate the impact of SAA passage on their operation. Further study revealed that the CdZnTe substrate on which the HgCdTe detector material was grown was the source of this glow and, for different reasons, Teledyne had developed a process to remove the substrate by thinning the detector. Subsequent fabrication of substrate removed detectors led to the use of FPA #129 in IR-1 during SLTV#2 in 2007. This part (see Figure 4 right) had more than 10% of its pixels brighter than the expected backgrounds but was otherwise acceptable.

With additional delays in the SM4 launch date, additional detectors were fabricated building upon experience gained earlier in the WFC3 project. FPA #165 was installed in IR-4 and FPA #159 in IR-3 as the final fight and flight-spare detector packages. As evident in Figure 4, IF-4 provides greatly improved sensitivity and much lower dark current than the earlier detectors.

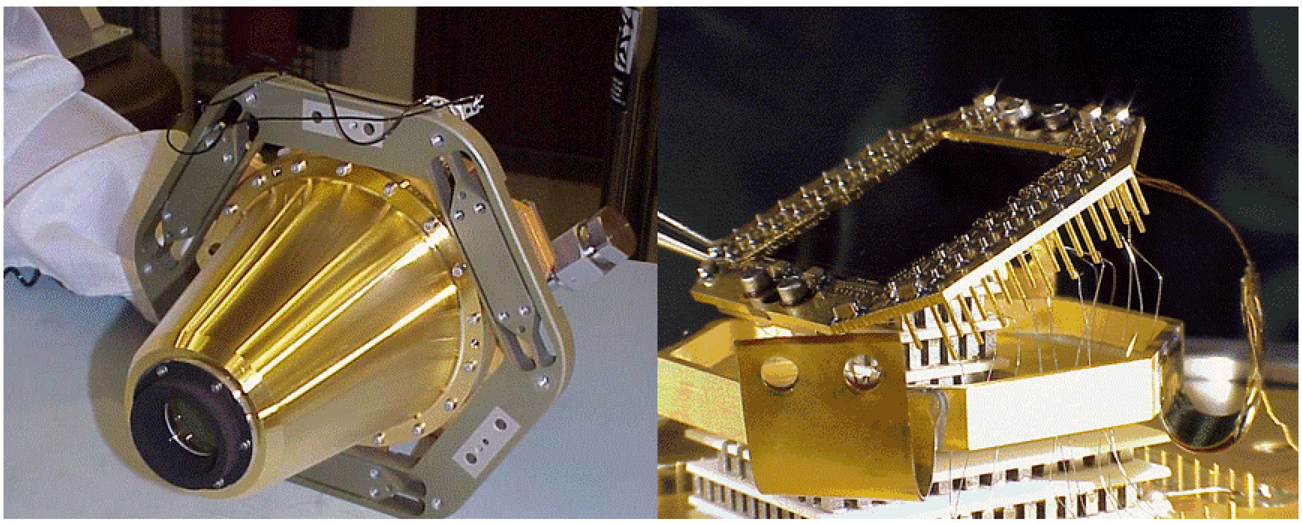

Figure 5. Infrared detector package (left) showing mounting ring. The IR focal plane mounted on the 6-stage thermal electric cooler is shown (right). The cup with flexure under the detector attaches to and cools an inner radiation shield to reduce thermal loading on the focal plane.

4.4 Instrument Interfaces

The interfaces between the detector packages and the rest of the WFC3 instrument are essential to their operation and potential for rapid changeout. The optical interface is carried through the interchange or mounting ring as discussed in Section 4.1. The thermal interface is a flexible heat pipe attached to the back of the package. This carried heat to the WFC3 external radiator directly for the UVIS detector and to the block of 1-stage TECs mounted on the radiator for the IR detector.

An additional key interface is the vent tube. Prior HST instruments used permanently evacuated and sealed packages for CCD detectors. To permit the use of materials that would not withstand the high temperatures required for permanently sealed packages, WFC3 elected to use plumbing that vents the detector package via holes in the WFC3 radiator. This required the astronauts to open two valves during the installation of WFC3.

5. IN-FLIGHT PERFORMANCE

The performance of WFC3 since its installation into HST has met or exceeded specifications. The instruments systems are operating on their primary side (i.e. full redundancy remains) and power consumption is close to expectations. The extensive experience of the team during three multi-month system level thermal vacuum tests proved valuable both in having operational issues well resolved prior to flight and in providing a solid foundation for instrument commissioning. The complex thermal system required to achieve the degree of cooling necessary for the detectors is working well. Both

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the expected thermal setpoints (at which the ground science calibrations were obtained) and the required stability in detector temperatures are consistently achieved. The image quality is excellent and the optical system has demonstrated very good long term stability.

One (pleasant) surprise is the throughput of the instrument is between 5% and 15% higher than expected from ground calibration. This is roughly a uniform increase in the IR channel and a smoothly varying increase in the UVIS channel (with the largest increase at visible wavelengths). This is larger than pre-launch expectations for the uncertainties in the absolute ground calibration of instrument sensitivity and remains unexplained.

5.1 Science Performance and Usage

WFC3 is used intensively by HST observing and accounts for approximately half of all science observations obtained and planned during the first two years following SM4. Following the success of the servicing mission, a special opportunity to propose very large scale investigations selected three major programs that rely mainly on the WFC3 instrument operated in conjunction with the ACS/WFC. This programs include multi-color mapping of key survey fields which have been examined by multiple space and ground telescopes, a survey of large galaxy clusters, and a program to image a large swath of the Andromeda galaxy from ultraviolet to infrared wavelengths. As the communities experience grows, the second round of selected programs resulted in a sizable increase in the usage of the infrared slit-less spectroscopy capabilities of WFC3.

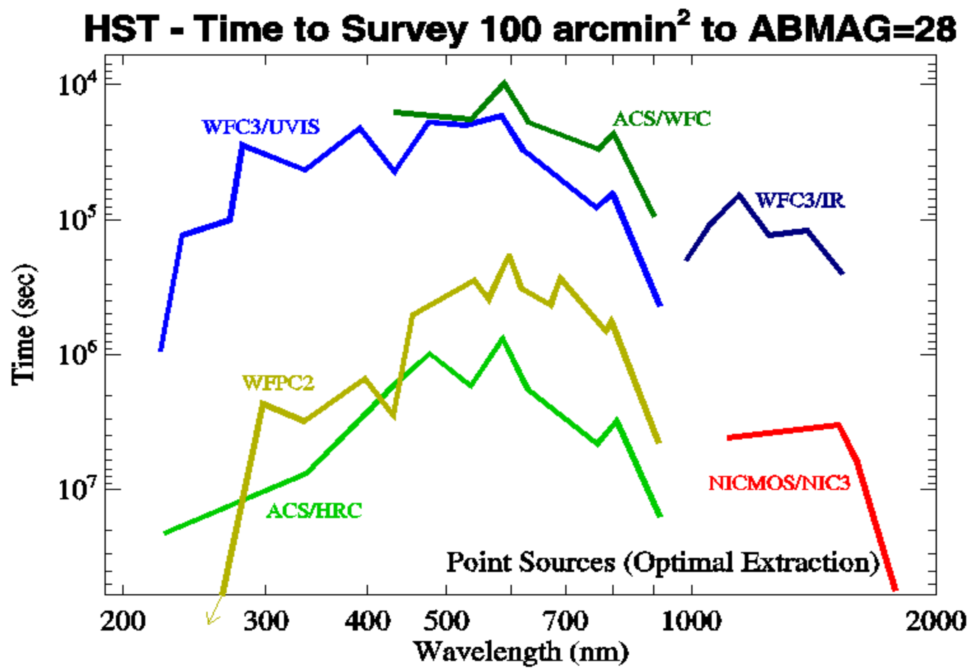

Figure 6. WFC3 provides HST observers with a dramatic (40-100x) increase in ultraviolet and infrared survey capability. The time to map a significant survey area (a major fraction of the HST science program is focused on projects of this nature) to 28th magnitude is shown. WFC3 is competitive with ACS/WFC, despite it 66% larger field of view, except in the 700-900nm region. For extended targets, the 25% larger pixel dimension of ACS/WFC improves its relative performance in the 500-700nm region at the cost of less spatial information.

5.2 UVIS Channel Performance

The detector performance is nominal and matches our prelaunch predictions. The UVIS channel readout noise is between 2.9 and 3.1 electrons (on the four amplifiers) and the dark current is far below the specification of 20 electrons per pixel per hour. Radiation damage cause two significant long term effects in the CCD detectors. It creates traps which decrease the efficiency of charge transfer (reducing photometric accuracy) and creates pixels with significantly enhanced rates of dark current production. As done with prior HST CCD detectors, the WFC3 CCDs are warmed monthly to anneal some of this damage. This proves to be successful in reducing the rate of growth in the hot pixel (elevated dark current) population (see Figure 7a). We measured (see Figure 7b) 1.5 e^- pix^{-1} hr^{-1} CCD dark current exclusive of "hot"

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pixels during ground testing but see ~2.5 e^- pix^{-1} hr^{-1} on orbit with a slow rise (currently projected to reach ~4 e^- pix^{-1} hr^{-1} by mid 2013).

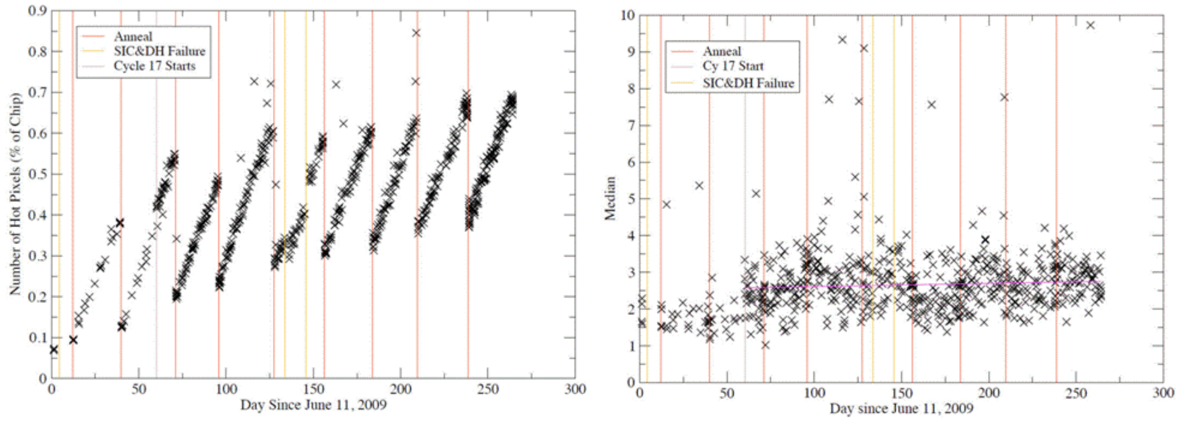

Figure 7. Period warmups to room temperature of the CCD detectors (vertical lines: red indicate planned and yellow unplanned) reduce the population of significantly hot pixels (left) although the cumulative impact of radiation damage is clearly visible. The bulk dark current is rising much more slowly and if the present trends continue will remain well below specifications for the remainder of the decade.

One concern prior to launch was the discovery of hysteresis in the quantum efficiency of the CCD detectors at the ~1 to 2% level. Ground experiments have now been demonstrated on orbit that periodic illumination (currently every 48 hours) with 475nm light to 0.5 million e^- pix^{-1} stabilizes this effect to better than 0.5%. Recent analysis studies have demonstrated that astrometric calibration is possible and stable to ~0.05 pixels or better, that it is possible to recovery photometry from saturated stars (although one of the CCDs performs better in this regard than the other for reasons not presently understood), and that the stability of the bias is extremely stable (over both days and many months).

5.3 IR Channel Performance

The IR detector performance in flight matches expectations. The dark current is slightly changed from ground calibration (level and distribution) but since the initial in-flight measures appears to be very stable.WFC3/IR meets it design goal of providing zodiacal light background limited observation in its broad band filters. The primary topics of investigation since launch are the management of image persistence, modifications to the data processing pipeline to better remove cosmic ray events, calibration of the rate dependent non-linearity, and this appear of 10-20 small blobs in the field of view.

The well known tendency of HgCdTe detectors to have elevated dark current following exposure to high light levels is present in the WFC3 IR detector. The great majority of science programs successfully manage this problem by taking multiple exposures with small shifts of the telescope pointing between each exposure (a.k.a. “dithering”). However, observations of brighter sources create residual images that persist for many hours and decay in a power-law fashion. Efforts are ongoing to (1) advise observers on optimal observational strategies, (2) identify those sources most likely to generate objectionable residuals and avoid scheduling WFC3/IR observations immediately after them, and (3) to develop post-observation software tools that generate appropriate dark calibration images.

On interesting phenomena is the complexity of the signal generated by the passage of cosmic ray particles through the IR detector. While such events are simply described for CCD detectors, the hybrid IR detectors (HgCdTe layer combined with a CMOS readout device) result in both positive and negative signals. Since the IR detector observations are obtained by resetting the detector and then obtaining a series (up to 16) samples of each pixel during the duration of the exposure, it is possible to flag discrete jumps in the accumulated signal. In practice, this has required considerable tuning of model parameters and is still imperfect.

As first observed with the NICMOS detectors, these devices require linearity correction both as a function of total signal level measured and also as a function of the rate of signal accumulation. This is a difficult measurement to make to high precision but quite important since the fundamental science calibration stars are 10,000 times brighter than many of the typical targets of scientific investigation.

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On early discovery that caused initial concern was the appearance of ~12 small (~25 pixel diameter) regions of decreased sensitivity (typically 10-20% decrease in the core of the features with soft edges). During the summer and fall of 2009 one to two such "blobs" appears monthly but no additional blobs have appeared since December 2009. An experiment in partially moving the Channel Selection Mirror (see Figure 1) demonstrated that the blobs reside on that mirror (which is very close to being in focus) and are not a detector issue. In total, the blobs span about 1% of all detector pixels (and may be partially calibrated in the future). At this time, 2.4% of all detector pixels show abnormal properties (e.g. low or no QE, high or unstable dark current, anomalous reset values, or blobs). Other than the blobs, these statistics appears very stable.

One minor (but not understood) phenomenon has been noted in the IR detector. While of no scientific consequence, the average level of the detector pixels following reset (i.e. the zero'th read level) has changed by about 20 DN ($50e^-$) during the first 250 days of operation.

6. INITIAL CALIBRATIONS

The calibration of WFC3 is a major task during its first year in operation and has consumed about 10% of HST's external observing time (heavily weighted toward the first couple of months of commissioning activities). These calibrations are divided into a period known as Servicing Mission Observatory Verification (SMOV) that concluded in September 2009 and Cycle 17 calibration that ran coincident with the 17th Cycle of scientific observations. The results of these calibrations are extensively documented on the WFC3 www site (http://www.stsci.edu/hst/wfc3), in a series of WFC3 Instrument Science Reports available on that www site, and in the revised version of the WFC3 Instrument Handbook (http://www.stsci.edu/hst/wfc3/documents/handbooks/currentIHB/wfc3_cover.html)

6.1 Photometric Performance and Calibration

As noted above, the sensitivity of the instrument is 5-15% higher than expected. As pertains to its calibration, over the first year of operation all broad and medium filters have been calibrated to 1-2% accuracy. The photometric stability of WFC3 UVIS since August 2009 is better than 0.5% and WFC3 IR is better than 1%. At this level of stability, it is becoming clear that the fundamental limitation for the photometric calibration of WFC3 in the visible will be the quality of the standard stars.

On area of caution with an ultraviolet sensitive instrument is loss of throughput at short wavelengths due to the deposition of molecular contamination on optical or detector surfaces or degradation of optical coatings or filters. Extensive monitoring over the first year in-flight demonstrates stability in the UV to better than 0.5% with no sign of a downwards trend.

6.2 Flat Field Calibration

The flat field calibration is a complex process due to the absence of ideal uniformly illuminated external sources in space. The present strategy for WFC3's flat field calibration is based on fully calibrating every filter during ground testing using an external illumination source and also with the instruments internal lamps. While the internal lamps do not provide very uniform illumination over the field of view, the plan was to employ them to detect and correct changes at the high spatial frequencies in the flat fields. In-flight, observations of dense star fields (mainly in the core of the globular cluster Omega Centauri) in multiple filters serve to calibration the low spatial frequencies of the flat field. We have obtained a 3x3 grid of observations of this star field at three roll angle over the first year of operations.

The star field derived low spatial frequency flat fields demonstrate that the ground external illumination system left about a 4% peak to peak residual error. The existing observations should correct this to <2% peak to peak and <1% rms with further improvements expected. All indications are that the instrument's flat field is very stable (<0.5%) based upon both monitoring with the internal illumination sources and the repeatability of the star cluster observations.

There are several limitations to the current flat field calibration approach. First, during testing of the UVIS detector package, the external surface of its window was contaminated with mineral deposits from water condensation. Unfortunately, this was not discovered until after the detector was installed into the instrument and systems levels calibration was underway. A difficult decision was taken to not remove and clean (or replace) the detector package. This was based upon (1) the value of the calibrations obtained during the systems level testing, (2) the superior performance of this detector package over the flight spare, and (3) care testing and simulation which showed that this contamination would have very minimal impact on scientific measurements. What it does impact is the value of the internal calibration

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lamps; in particular, their utility for correcting any changes in the high spatial frequency flat field. Fortunately, so far very little change has been observed.

Second, limitation in the ground calibration equipment required that the ultraviolet flat fields (<300nm) be obtained in air with the CCD detector operating at ~-50C (rather than its nominal -83C operating temperature). Combined with fairly significant flat field features at medium and low spatial frequencies in the UV, this limits the quality of the UV flats compared to the flat at wavelengths >300nm. Given the further limitation on finding suitably dense collections of UV sources, the long term prospects for reaching sub-1% are uncertain.

Another approach to obtaining high quality flat field calibrations over all spatial frequencies it to observe extended external sources. For ground observatories, the night sky and/or the inside of the telescope dome usually serves this purpose. For WFC3, the "night sky" (actually the scattered sunlight from zodiacal dust) is too faint to create sufficient flux per pixel in any UVIS channel filter but does produce a significant signal (~1 e^{-} pix^{-1} s^{-1}) in the broadest IR channel filters. The stacking of all long exposures in those filters to date which do not contain bright sources offers an alternative path to a flat field calibration. At this time, this calibration is sufficient as a cross check on the results of the star cluster derived low spatial frequency flat field and is reasonably consistent.

A second alternative is to use the earth as a source. This has been done, with mixed results, with prior HST instruments. Unfortunately, WFC3 is too sensitive in its broad filters (especially in the infrared) and the earth is a poor UV source and also rather non-uniform. During the coming year, the usefulness of this technique will be tested. On variant under consideration is the observation of the dark earth when illuminated by the moon. Given the 50 degree solar exclusion angle constraint on HST, this is difficult but not impossible to schedule.

6.3 Astrometric Calibration

The relative positions of pixels and their position relative to the HST focal plane are key calibrations. One design compromise in WFC3 was the acceptance of a significant amount of image distortion. This was necessary to achieve the desired field of view while simultaneously fitting the instrument within the physical envelope permitted by the WF/PC-1 enclosure.

Using observations of star fields within 47 Tuc and Omega Cen for which high precision astrometry already exists, relative astrometric calibrations have been achieved with residuals of ~ 0.05 pixels in 10 UVIS and 5 IR filters. With these calibrations, the multi-drizzle software developed at STScI can combine images in the same or different filters to ~0.1 pixels over the entire field of view and project the image onto a rectilinear grid.

7. LESSONS LEARNED

7.1 Interchangeable Detectors

The most significant decision taken in the definition of WFC3 was probably the requirement for rapidly swappable detector assemblies. As discussed in Section 4, this supported both recovery from problems and allowed WFC3 to use numerous delays in the mission launch date to continue to enhance its infrared detector. From a programmatic perspective, reducing the coupling of the highest risk components from the critical path repeatedly proved a wise decision.

7.2 Light Control for Infrared Detectors

The decision to rely solely upon electronic gating for exposure control of the infrared channel has some negative consequences. First, the full illumination history of the detector is unavailable (e.g. bright sources move within the field of view during dithers and the detector is often exposed to sources of unknown spectral energy distribution in a series of filters during filter wheel motions). Since the infrared detector has persistence, imperfect of knowledge of recent exposure limits the ability to correct for the persistence. Further, the absence of the shutter is most acutely noticed when making observations of very bright sources since the usual strategy of dither is degraded and measurements in multiple filters are impacted by the proceeding observations.

Also, to avoid exposing the IR detector to the bright earth (HST views the earth in nearly every orbit since it slews quite slowly), WFC3 moves the IR filter wheel (which contains a solid "blank" element) at least twice per orbit. Although this mechanism was designed for this application, it would have been possible to design a shutter with higher mechanical reliability for this purpose.

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7.3 Filter Characterization

During the first system level optical tests of WFC3, it was discovered that numerous filters in the UVIS channel produced discrete optical ghosts well beyond the specifications. Although these filters utilized the latest technology, were carefully built, and their transmission properties fully characterized, this had escaped detection. The unfortunate delays in SM4 provided time to disassemble the SOFA and replace nearly all of these filters. A nearly exact mock-up of the WFC3 optical system was created and all of the new and spare filters fully tested under appropriate optical conditions. In particular, many ghosts are insignificant in white light but are a serious issue when the filter is illuminated with light mainly at one side of its pass band (e.g. due to a source with a strong emission line or having extreme color). Naturally, these represent some of the most unfortunately situations for ghosts to be present from the perspective of the observer. Once again, the old rule of "test as you fly" is validated.

7.4 Internal Calibration System

The internal calibration system of WFC3 provided full field illumination of the UVIS and IR channels using Tungsten and Deuterium lamps. For reasons of cost and physical space within the optical bench, this system was not required to provide: uniform illumination, full utilization of the entire optical path of WFC3, or to match the f/ratio of the WFC3 optical beam – it was sufficient to illuminate the detector through the filters with less than a factor of 2 variation in illumination level.

This system was very useful during initial system checkout because it decouples many activities from the telescope and it is moderately useful for long term monitoring. However, as discussed in Section 6.2, it has serious limitations for flat field calibration. This required increased reliance upon quality ground calibrations and long term instrument stability. While this may yet prove to work satisfactorily, avoiding such dependencies is a good idea. For example, a late swap of the UVIS detector would have forced WFC3 to fly with a permanently inferior flat field calibration.

7.5 Thermal Systems

The use of TECs to cool both the CCD and IR detectors was certainly pushing the envelope. This had at least three major implications for the development of the instrument.

First, WFC3 developed (with Teledyne Scientific) a new infrared detector with a 1.7 micron long wavelength cutoff. As discussed in Section 4.3, this was arguable the tall pole in this project. This cutoff was selected to achieve two goals: the detector is insensitive to thermal radiation from sources cooler than ~-25C and has acceptably low dark current when operated at ~150K. Compared to prior 2.5 micron long wavelength cutoff HgCdTe detectors which must be baffled from thermal radiation and are operated at 77K, this simplified the WFC3 thermal requirements but they remained very challenging. Throughout the WFC3 design and development phase, there was probably only about 5 degrees K margin between the capability of the instrument to cool the infrared detector and the cooling required to operate the detector at a scientifically useful temperature. This represented a high degree of risk in that neither subsystem had margin to assist the other if it had gotten into an unsolvable situation.

Second, WFC3 has limits to both into input power and its permitted thermal rejection via paths other than its dedicated radiator. This led to a design that grew in complexity (multiple layers of TEC cooling, spreader heat pipes to maximize the efficiency of the radiator). Such a system is difficult to model in the extreme. In fact, the WFC3 thermal model is still not fully correlated even after a year in operation. Consequently, at each stage in the design, development, testing, and flight of WFC3, it has been difficult to assess the margins present in the thermal design and thus difficult to avoid increasing complexity.

Third, this complex thermal system was very difficult to test on the ground. Creating realistic thermal environments on a complex system carries the risk of being both insufficiently and overly conservative. Many fragile component were certainly not able to sustain excessive testing – this may have been the cause of the damage to the 4-stage TECs in both the flight and spare UVIS detector packages prior to SLTV#2. Further, heat pipes behave differently under gravity unless oriented horizontally. This became a design requirement that could not always be met (e.g. vertical spreader heat pipes on the radiator resulted in a separate set of tests on the radiator subsystem and modeling of the complete system performance). This again drives the balance between realistic testing and margin (hence system complexity).

In-flight, the WFC3 thermal systems have performed very well and are a great credit to the thermal and systems engineers and technicians would labored to develop them.

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8. SUMMARY

The Wide Field Camera 3 is successfully installed and operating on the Hubble Space Telescope. As HST's most recent camera, it continues to Hubble's extraordinary history of producing images remarkable for both their scientific value and their appeal to larger community. WFC3 is an ongoing project whose calibration and characterization continues to improve. Additional information is available at www.stsci.edu/hst/wfc.

9. ACKNOWLEDGEMENTS

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