Calibration of the Hubble Space Telescope’s Wide Field Camera 3 (WFC3): a case study

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WFC3 focal plane
WFC3
Just the beam
UVIS Channel

2 CCDs, 4 amplifiers, 5 filter wheels
62 filters – broad band, medium band, narrow band, monolithic and ‘quad’
1 grism
WFC3 in HST
Pre-Flight Calibration

- **Thermal Vacuum tests**
  - fully assembled instrument placed in thermal and vacuum controlled test chamber
  - operated in simulated flight conditions
  - calibrated light source(s) puts light into the optical path of the instrument
- **CASTLE** (Calibration Stimulus from Leftover Equipment)
Pre-flight Ground Testing

TV2 & TV3 provide:
• initial set of dark and bias files
• initial flat fields for all filters
• the only spectroscopic flat fields
  – monochromatic flats
• checks on the
  – wavelength response
  – filter transmission
• detector characteristics:
  – Readnoise
  – Intrapixel sensitivity variation
  – Quantum efficiency
  – Hysteresis (Bowtie)
  – Persistence

Pre-flight data provides first pass to development of the ETC, and Synphot, used subsequently to develop observing programs
G280 Grism TV3
UVIS Grism G280- TV3

WFC3/UV G280 chip 1 (TV3 Mar 2008)

WFC3/UV G280 chip 2 (TV3 Apr 2008)

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“bowtie” and shutter edge effect

Figure 2: At right is a hard stretch (+/- 1%) of an image ratio of two F814W images taken within 14 hours of each other, illustrating low-level shutter edge effects (the slanted lines which appear to emanate from the upper right, B amp corner). At left is an image ratio of two F555W images taken about 26 hours apart, showing the CCD ‘hysteresis’ effect. Stretch is +/- 10%.
Data processing Flow Chart
In-Flight Calibration Activities

• SMOV
  – Service Mission Observatory Verification
  – Service Mission 4B in May 2009
  – 3 month commissioning May – August 2009

• Regular Cycle Programs
  – Cycle 20 ~9/2012 – 8/2013
  • NB: Cycle ‘boundaries’ are fuzzy
Basic operation checkout
First light image
Initial checks on throughput, image quality, flat fields, linearity, zeropoints, bad pixels.
Establish baseline for darks, biases, charge transfer efficiency, sensitivity (stability).
Fringing test – jupiter impact
=> nominal behavior, met specs.
PSF Characterization

Encircled energy vs. Radius (arcsec)

Left: UVIS F275
Right: IR F160W

PSF WINGS

Left: UVIS F275W
Right: IR F160W

20 x 20 arcsec, 6 dex log stretch
Read Noise Improved vs. Ground Test

- CDS read noise is 20–22 e- rms (varies with quadrant); same as ground result; noise in RAPID reads also similar to T-V result.
- Effective noise reading up the ramp is actually a bit lower in flight than in thermal-vac for long exposures: (average of the 4 quadrants shown)

<table>
<thead>
<tr>
<th># of Reads</th>
<th>3</th>
<th>8</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective noise (e- rms; SMOV)</td>
<td>19.6</td>
<td>16.0</td>
<td>12.4</td>
</tr>
<tr>
<td>Effective noise (e- rms; thermal-vac)</td>
<td>20.8</td>
<td>17.8</td>
<td>14.6</td>
</tr>
</tbody>
</table>

- Combined with excellent dark current, very well satisfies goal of being zodiacal-background-limited for long exposures in broad bands (zodi rates from a few tenths to >1 e- /pix/s)

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Fringing in CCDs

F673N flat field (quadrant B)

FQ937N flat field (quadrant B)

Histogram (pixel count)

Pixel value

0.8 0.9 1.0 1.1 1.2 1.3

F673N

2.5x10^4

2.0x10^4

1.5x10^4

1.0x10^4

0.5x10^3

0 5.0x10^3

FQ937N

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Fringe model vs. data

- TV3 Data (21° incidence)
- DCL Data (0° incidence)

Graph showing the comparison between the fringe model and the data for different incidence angles.

Wavelength (nm)

- TV3-based model, for 21° incidence
- DCL-based model, for 21° incidence
- DCL-based model, for 0° incidence
- TV3-based model, for 0° incidence

Fringe amplitude
Detector thickness
Post SM4 Calibration Activities

- Monitor instrument behavior
  - CCD
    - Charge transfer efficiency
    - Readnoise
    - Pixel response
    - Linearity
    - Geometric distortion
    - Image quality (PSF)
  - HgCdTl
    - Intrapixel variation
    - Linearity
    - Count rate non-linearity
    - Geometric distortion
    - Image quality (PSF)
  - Contamination
    - UV, outgassing
  - Photometric stability
    - Zeropoints
    - Flat fields – pixel to pixel, low frequency spatial variation
Building Calibration Programs

• Goal:
  - Provide calibrations to match PI science objectives and optimize HST / WFC3 science

<table>
<thead>
<tr>
<th></th>
<th>Cy17</th>
<th>Cy18</th>
<th>Cy19</th>
</tr>
</thead>
<tbody>
<tr>
<td>WFC3 of HST total</td>
<td>46.1</td>
<td>41.9</td>
<td>48</td>
</tr>
<tr>
<td>IR Imaging</td>
<td>24.4</td>
<td>5.5</td>
<td>11.4</td>
</tr>
<tr>
<td>IR spectroscopy</td>
<td>6.7</td>
<td>15.9</td>
<td>2.7</td>
</tr>
<tr>
<td>UVIS imaging</td>
<td>15</td>
<td>15</td>
<td>26.4</td>
</tr>
<tr>
<td>UVIS spectroscopy</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>0.9</td>
</tr>
</tbody>
</table>

as percentage of total HST orbits per cycle
Building Calibration Programs

- **Daily**
  - Dark frames – for each detector, subarray and exposure modes
  - Biases -> superbiases
- **Weekly**
  - Flats – for every filter utilized
    - internal tungsten lamps
    - star clusters
- **Monthly**
  - Anneals
- **Least Frequent:**
  - Monitoring programs, new programs
    - Wavelength calibration
    - Flux calibration for each detector, filter & grism
    - Photometric stability
    - Geometric distortion, PSF
    - Persistence
    - Charge transfer inefficiency
    - UV contamination
Building Calibration Programs

Calibration Sources:
1. Lamps (QTH & Deuterium))
2. Basic Set of Astrophysical sources
   1. Omega Cen
   2. 47 Tuc
   3. GD73, GD153, G191B2B, P330E, & GRW70

Calibration Hardware:
back of the channel select mechanism
otherwise None!
Cycle 17 Activities

Primary programs
• characterization of
  – geometric distortion,
  – zeropoints,
  – sensitivity
  – filter transformations;
• daily monitors
  – detector gain,
  – darks and biases;
• monthly anneals (CCDs),
• “bowtie” pinning
• checks on persistence on the IR detector (MCT),
• count rate nonlinearity
• flats.

Additional checks on
• IR persistence
• Additional fringe calibration
• Check subarray linearity
• Determine image skew wrt to fixed stars – astrometry
• Stray light
• Test spatial scanning mode

Orbit allocation
• 256 external orbits
• 2000+ internal orbits
Cycle 18 Programs

- Regular monitor programs – darks, bias, anneal, stability, bowtie
- Expand photometric standard sets – more spectral types
- Improve color transformations
- Calibration of scanning modes – photometry and spectroscopy (enables bright object to $V \approx 0$ mag)
- High contrast imaging tests (e.g., exoplanets)

Additional tests for
- Persistence – correction file
- Flat field tests – raster scanning of a standard star.
- CTE mitigation

- ~150 external orbits,
- ~1900 internal orbits
Cycle 19 Programs

- Regular monitor programs – darks, bias, anneal, stability, bowtie
- Photometric calibration ladder
- Calibration of scanning modes minus orders (flux, wavelength)
- Spatial scans of stars to test flat fields and improve astrometry
- Earth flats

Additional tests for
- Charge injection (mitigate CTE)

~125 external orbits
~1587 internal orbits
So, What Do We Know?
Count rate non linearity (‘reciprocity failure’) depends on brightness and wavelength of source. Bright sources are brighter, faint sources are fainter. i.e. $10 \times 100 \neq 100 \times 10$
Count Rate Non Linearity
WFC3 - NIC

Results:

- F110W:
  \(0.01 \pm 0.0022\) mag/dex

- F160W:
  \(0.011 \pm 0.0022\) mag/dex

- F098M:
  \(-0.065 \pm 0.0031\) mag/dex
Observations over 7 epochs show no statistical change in the UV response. Errors bars are formal statistical errors.
Persistence

LHS: guard dark, RHS: an MCT observation
Grism observation was taken 1 hour before
Persistence

**Latency**

![Graph showing latency](image)

**Decay rates**

![Graph showing decay rates](image)

Figure 1 - The persistence as observed individual pixels in a dark exposure shortly after the 3R detector had been illuminated by a very bright star, in this case Fomalhaut. The x-axis shows the illumination in electrons of the last of the Fomalhaut exposures while the y-axis shows the persistence in e^-s^-1. The red vertical lines show the five levels to which the array was illuminated with the Tungsten lamp in this calibration program.
Flat fields and Ghosts
Model of Ghost Flares
Linear Distortion stability

UVIS

IR

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Observed vs. Predicted Sensitivity

UVIS: 5-10% boost in efficiency at blue/red $\lambda$'s, 15-20% at 400-700 nm

IR: 10-15% boost in efficiency at all $\lambda$'s
Photometric Stability \(~0.5\%\)
WFC3/IR Grism Flux Calibration Stability:

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G102 Grism

![Graph 1: Position vs. Wavelength](image1)

![Graph 2: Total Transmission vs. Wavelength](image2)

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WFC3 Photometric Calibration and Calibration Flux Ladder

Objective:
Improve the absolute photometric calibration and cross-calibration of user grism and imaging observing modes
Minimize uncertainties due to models, drive absolute calibration to <0.5%.

Description of the observations:
Direct images of 4 CALSPEC standards (UVIS & IR) & V>14 mag
Spatial scans 9< V < 13 mag stars: IR grism and imaging

Targets: STIS, ACS, NICMOS, SPITZER/IRAC, and JWST standards.
P330E, VB8, GD71 and GD153

A-type stars: HD165459 (A4V), 1732526 (A4V), 1740346 (A6V), 1743045 (A8II), 18032271 (A2V), 1805292 (A4V), 1812095 (A5V)

G-type stars: HD209458 (G0V), P041C (G0V), P177D, SNAP-2 (GO-5)

Other: 2M0036+18 (L3.5), 2M0559-14 (T5), KFO6T2 (K1.5III)
Vega in the G141 Grism

- Scanned spectra of Vega with both IR grisms.
- Vega placed in 3 positions on the array
- Scan rate = ~5 arcsec/sec and 7 arcsec/sec.
Lessons learned

• Expect change
• No atmosphere in space – good
• Radiation, shake `n bake – not so much
• Illumination corrections are doable in orbit for imaging
• Stray light is insidious
• Some basic calibration hardware is essential
  – Even IR detectors need a mechanical shutter for darks
• Innovation is essential
  (especially when NASA SMD Associate Administrator
  John Grunsfeld can’t get to orbit and add hardware)
The WFC3 Scientific Oversight Committee

- Bruce Balick, University of Washington
- Howard E. Bond, Space Telescope Science Institute
- Daniela Calzetti, Space Telescope Science Institute
- C. Marcella Carollo, Institute of Astronomy, ETH, Zurich
- Michael J. Disney, Cardiff University
- Michael A. Dopita, Mt Stromlo and Siding Spring Observatories
- Jay Frogel, AURA
- Donald N. B. Hall, University of Hawaii
- Jon A. Holtzman, New Mexico State University
- Randy Kimble, NASA Goddard Space Flight Center (ex officio)
- Gerard Luppino, University of Hawaii
- Patrick J. McCarthy, Carnegie Observatories
- John MacKenty, Space Telescope Science Institute (ex officio)
- Robert W. O’Connell, University of Virginia (Chair)
- Francesco Paresce, European Southern Observatory
- Abhijit Saha, National Optical Astronomy Observatory
- Joseph I. Silk, Oxford University
- John T. Trauger, Jet Propulsion Laboratory
- Alistair R. Walker, Cerro Tololo Interamerican Observatory
- Bradley C. Whitmore, Space Telescope Science Institute
- Rogier A. Windhorst, Arizona State University
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Olivia Lupie
André Martel
Brian McLean
Abhijith Rajan
Neill Reid
Massimo Robberto
Michael Robinson
Megan Sosey
Massimo Stiavelli
Michael Wong

- WFC3 Management, Engineering, and Contractor Teams
- Thai Pham and Jackie Townsend, GSFC Instrument Managers
- GSFC Engineering Teams in Codes 400, 500, and 600 (plus Code 300 reviewers)
- Ball Aerospace, Swales Aerospace (now ATK), Teledyne, E2V, and many others

300-400 people made significant contributions to the development of Wide Field Camera 3
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