WFIRST Coronagraph calibrations overview

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Brian Kern
Jet Propulsion Laboratory
California Institute of Technology

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Overview

- Categories of calibrations
- Detectors
- Imaging
- IFS
- LOWFS + C
- High-order wavefront control (EFC)

Categories of calibration

- Different calibrations are performed with different frequency
  - Ground-based (pre-flight)
  - Initial in-flight checkout
  - Per target
  - Per mode (wavelength band, SPC orientation, etc.)
- Different subsystems each have calibration requirements
  - Imaging science camera
  - IFS
  - LOWFS
    - Includes alignment of focal plane mask to star
  - High-order wavefront control (EFC)
    - Includes alignment of SPC to pupil, HLC + SPC Lyot stop alignment to pupil
    - Common to both imaging and IFS modes

Calibrations vs. frequency

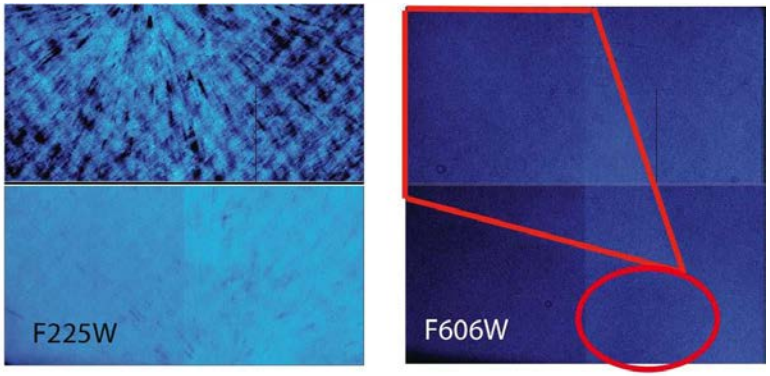
		months-year	days-weeks	hours-days
	Ground based	**Initial / few**	**Per target**	**Per mode**
LO + DI + IFS flat field	✓	?		
IFS λ registration	✓	✓	?	
DI + IFS dark/hot pix	✓	✓	✓	?
DI + IFS traps	✓	✓	?	?
Mask alignment	✓ -	✓	?	?
LOWFS capture/align	✓ -	✓	✓	✓
Phase retrieval	✓ -	✓	✓	?
Star-DI + IFS registration	✓ -	✓	✓	✓
EFC	✓ -	✓	✓	✓

Detectors

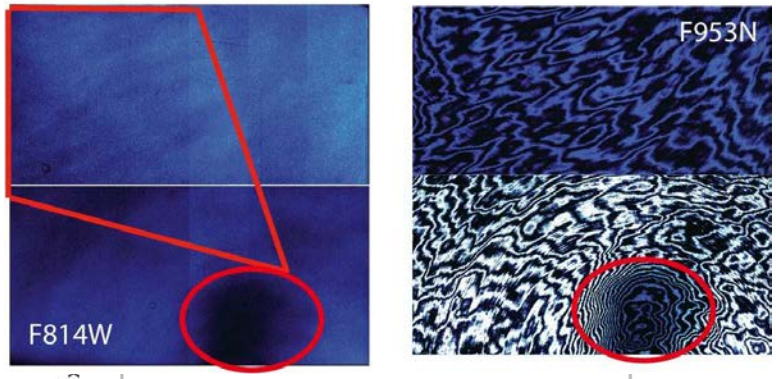
- 3 detectors on CGI
  - DICAM (Direct Imaging), IFSCAM (IFS), and LOCAM (LOWFS)
  - All three are thinned, back-illuminated AR-coated CCDs
- Detectors need to be calibrated for variation in sensitivity
  - Function of (x,y) location and wavelength λ
    - Flat-fielding
  - Monitor for contamination / changes over time
- Detectors need to be calibrated for registration
  - At what (x,y) does "star center" land on DI, IFS, or pupil center for LOWFS
  - How do wavelengths map to (x,y) on IFS
- Detectors need to identify hot pixels (dark current)
  - Changes with time due to radiation damage
- Strong interest in identifying locations / properties of traps on CCD
  - Not clear how to feed back knowledge of traps to improve measurement
- Relevant question: is in-flight internal source required for calibration?
  - Internal calibration source is not in official baseline yet

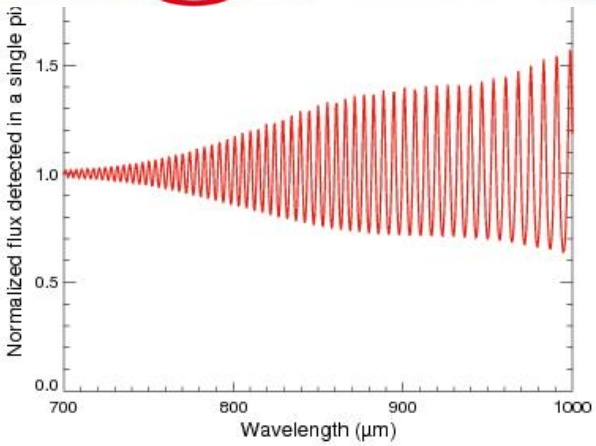
CCD flat field generic expectation

- WFC3 experience on HST:
  - Ground-based calibration left ~ 2-5% rms broadband photometry errors
    - 10-pix radius aperture (40 mas/pix)
  - After on-orbit revision, 1% accuracy for $\lambda < 850$ nm, ~ 2-3% accuracy
  - This is accuracy relevant for direct imaging and LOWFS
- For thinned, back-illuminated CCDs at long wavelengths, fringing is dominant problem
  - Rapid change with wavelength
    - Broadband effect is small
  - 770 nm ~ +/- 10%
  - 890 nm ~ +/- 30%
  - Stable over time (pre-flight to on-orbit)
  - This effect is most relevant for IFS
    - Lenslet spectrum ~ 25 pix × 2 pix



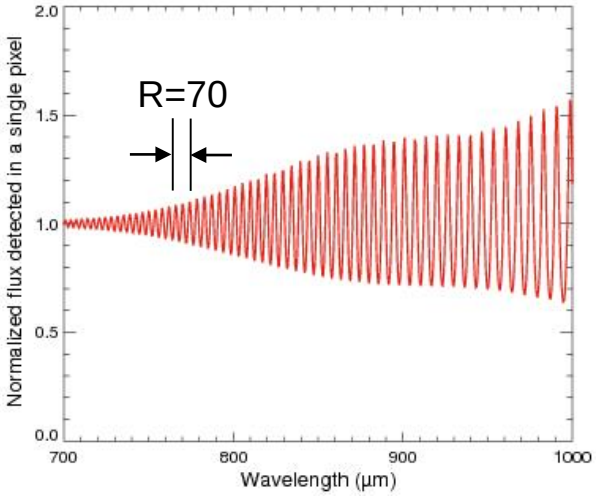
http://www.stsci.edu/hst/wfc3/documents/handbooks/currentIHB/c05_detector5.html





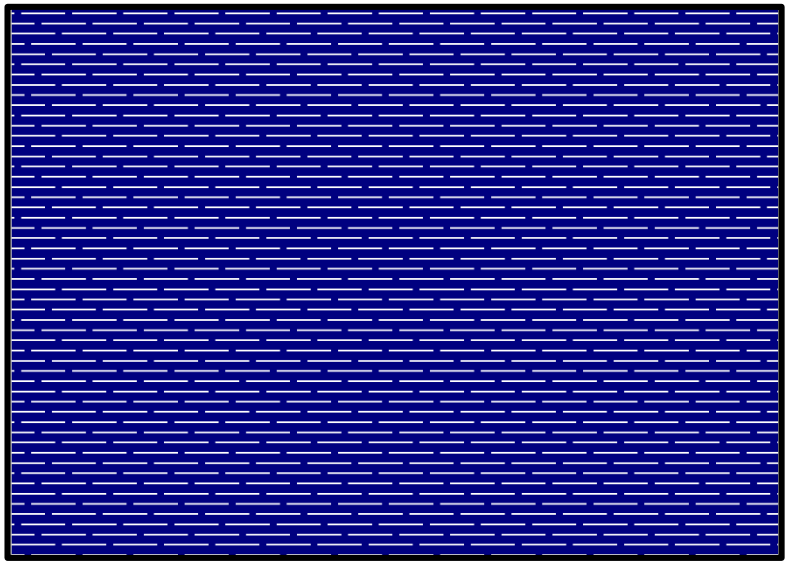
CCD flat fielding requirements

- For direct imaging, SNR=5 requirement likely implies ground-based flat fielding is enough
  - WFC3 had no internal flat-fielding source, but calibrated photometry to < 1% for broadband, short-wavelength filters
  - Should quantify effect of smaller photometric aperture (~ 1 pix radius for CGI versus 10 pix radius for WFC3)
- For IFS, fringing at R=70 will vary response by several % in λ = 770 nm filter
  - Need to check real-world experience of variation from ground-based measurements to flight to see if ground-based is sufficient not to limit SNR=15 per resolution element
  - Astrophysical calibration may be an option to calibrate relative flux across spectral resolution elements
    - Elliptical galaxy continuum for extended object?
  - Fringing will be larger for λ = 890 nm filter
- What about "guest observing?"



IFS wavelength calibration

- Position / orientation of lenslet spectra need to be calibrated
  - Ideal would be 3 narrow wavelengths across each 18% IFS band
    - 3 wavelengths x 3 filters x ~ 400 lenslets = 3600 calibration points
- Ground-based calibration can likely accommodate a large range of narrow wavelengths
  - Narrow filter on supercontinuum source?
  - Tunable laser?
- Changes in CGI bench during launch and in flight are likely to be large-scale (low order) variations
  - Can they be described as (x,y) offset and x-scale, y-scale factors across entire detector (4 parameters)?
  - Include roll (5 parameters?)
  - Include disperser roll (6 parameters)?
  - Variation on what timescales?

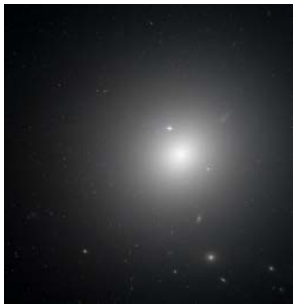


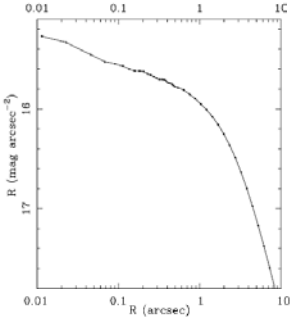
PISCES (IFS testbed) lenslet spectra geometry

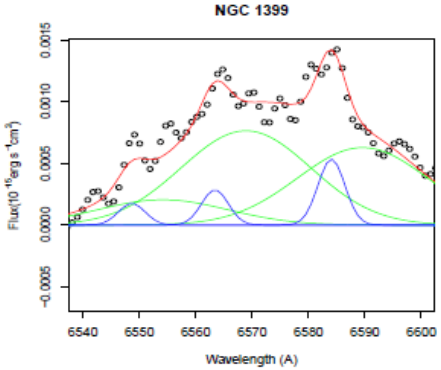
https://alpha-lib.jpl.nasa.gov/docushare/dsweb/Get/Document-1112230/McElwain_PISCES_AFTA-C_PR_FINAL.pptx

Open questions for IFS calibration

- Are there science requirements on wavelength accuracy?
  - This question is loosely coupled to SNR=15 requirement
  - 1% absolute wavelength registration? 2%?
  - Can we use only astrophysical references?
    - Cores of elliptical galaxies are extended > 1 arcsec, many have Hα spectral line
    - Observable with SNR ~ 20 per spatial + spectral element in ~ 1 hr







https://en.wikipedia.org/wiki/NGC_1399

http://iopscience.iop.org/article/10.1086/522938/pdf

https://www.gemini.edu/gsm12/pdf/gsm2012_poster_ricci-tiago.pdf

    - White dwarf can give featureless spectrum for wavelength flat field, V ~ 12

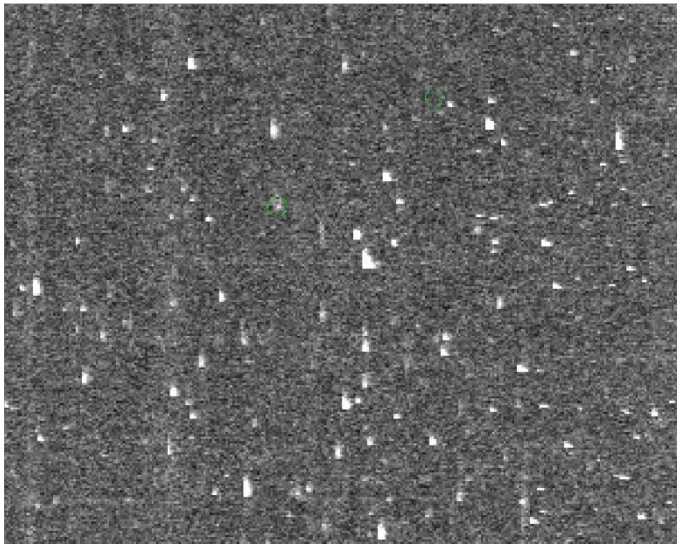
- Are there situations where absolute calibration beyond SNR=15 will be required?
  - Disc science won't care about IFS?
  - "Guest observer" science does not impose requirements?

Dark current and traps

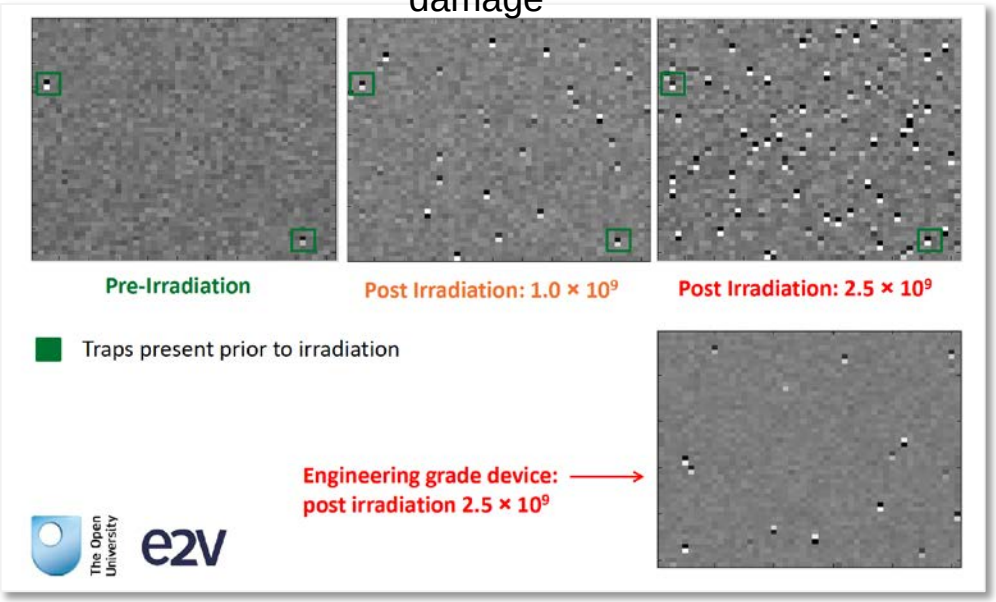
- Dark current, hot pixels, and traps are increased by radiation damage
  - Degradation will likely not be at some constant rate
  - WFIRST experience at L2 will likely be very different than HST in LEO
- Identification of dark current / hot pixels very relevant to planet SNR
  - For long observations with IFS, hot pixel distribution will likely change during observation
- Knowledge of locations of traps may or may not affect observing + data analysis practices

https://alpha-lib.jpl.nasa.gov/docushare/dsweb/Get/Document-1557049/MS-7_Final.pptx

dark current after radiation damage



traps after radiation damage

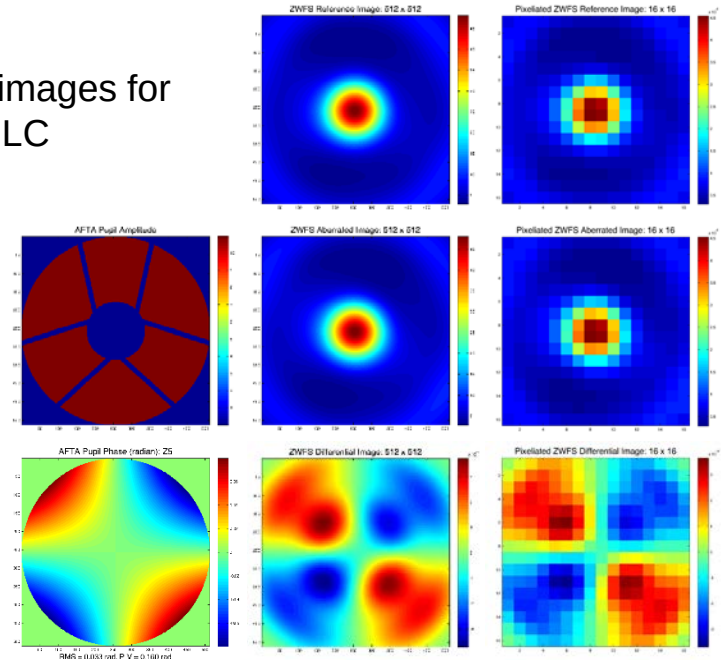


Mode-specific calibrations

- LOWFS/C operates on differential images
  - Acquire a reference image and drive sensed low-order modes to return to state of reference image
- Reference image can be taken to preserve any particular high-order wavefront control state

https://alpha-lib.jpl.nasa.gov/docushare/dsweb/Get/Document-1316167/Coronagraph_Milestone6_Slides_29Sept2015_backup_fs.pptx

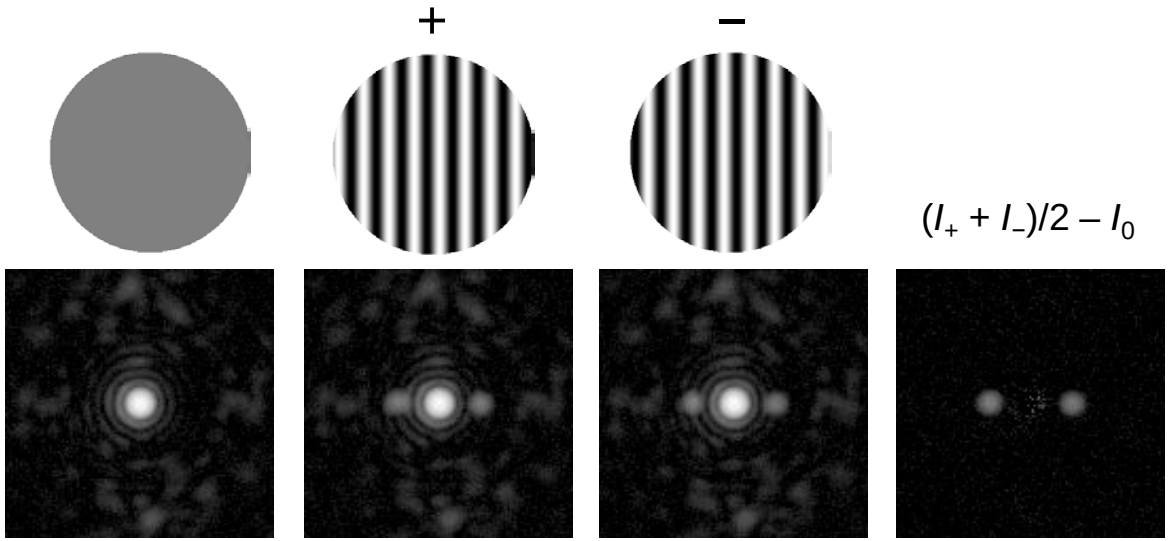
LOWFS images for HLC



- Direct imager has polarization splitter in at all times
- Ground-based polarization calibration is likely good in flight to ~ few percent accuracy
  - SNR of Stokes measurements for planets will likely be low
    - Planet measurements will not reach accuracy limits

Registration of star to camera

- Star is coronagraphically blocked and controlled by high-order wavefront control
  - Astrometric location of star is not contained in science images
- Testbed experience has been good with +/- speckles
  - Sine wave on DM, both + and – amplitude
  - Mean location of “speckles” is star center
  - Good to < 0.01 pix on testbed
  - Can be made bright, use little exposure time

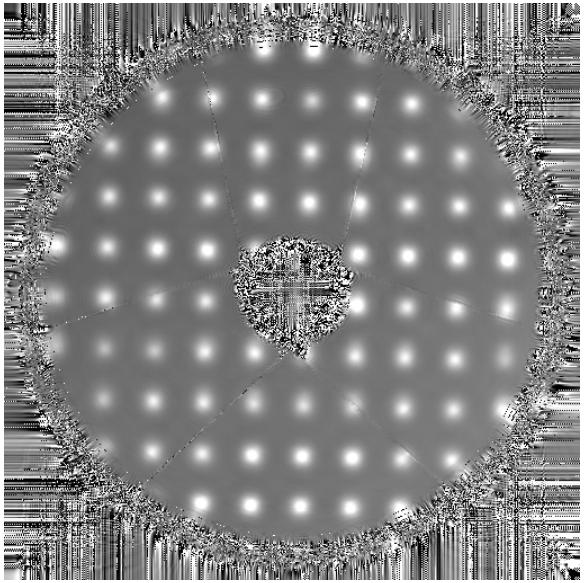


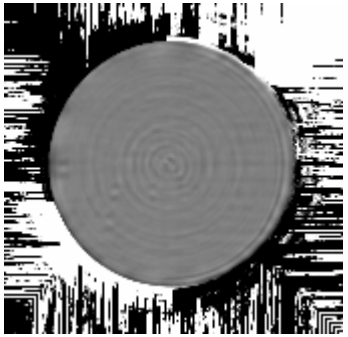
https://exoplanets.nasa.gov/exep/files/exep/PIAAMilestone1.pdf

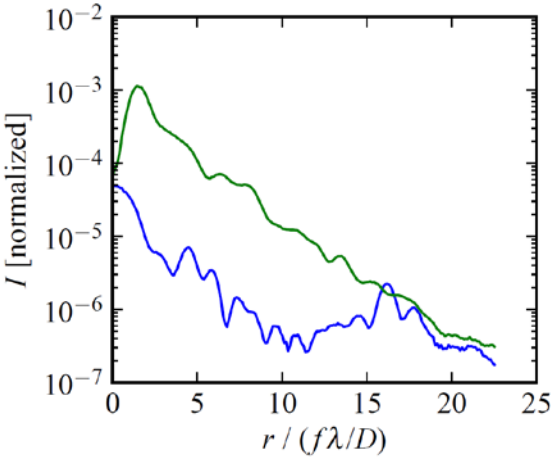
High-order WFC calibrations

- Ability to find WFC solution for DM requires accurate model inputs and alignment
- Dominant tool for registration and wavefront estimation is phase retrieval
  - Depending on spatial frequencies, phase retrieval accuracy is ~ 1 mrad in phase for mid-spatial frequencies
  - Can locate actuator positions to ~ 50 um each
  - Fit "array" of actuators to ~ 10 μm

https://alpha-lib.jpl.nasa.gov/docushare/dsweb/Get/Document-1470042/20151029phaseretrievalfromarchives.pptx







Conclusions

- Regarding flat-fielding and wavelength accuracy
  - Need more detailed science requirements for wavelength accuracy
  - Need to know from science requirements if flat fielding will be required at accuracy < few percent
  - Need STOP models to show how much coronagraph bench, notably downstream of IFS optics, will misregister images

- Questions:
  - Wavelength accuracy?
  - Flat-fielding floor (systematic flux vs. position errors)?
  - Requirements on astrometric accuracy:
    - Fundamentally problematic near IWA