Nancy Grace Roman Space Telescope Coronagraph Instrument Observation Calibrations

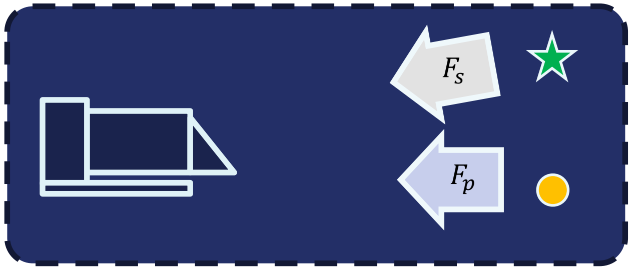
Rob Zellem[1] (he/him), Bijan Nemati[1,2],
Vanessa Bailey[1], Eric Cady[1], Mark Colavita[1], Ewan Douglas[3], Guillermo Gonzalez[1], Tyler Groff[4],
Sergi Hildebrandt[1], Bertrand Mennesson[1], Erin Maier[3], Marie Ygouf[1], Neil Zimmerman[4]

With support from many at the Jet Propulsion Laboratory, Goddard Space Flight Center, and the Science Investigation Teams

1 Jet Propulsion Laboratory – California Institute of Technology
2 University of Alabama – Huntsville
3 University of Arizona – Steward Observatory
4 Goddard Space Flight Center

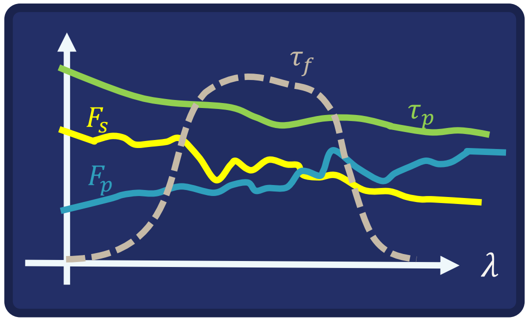
Flux Ratio

- Flux ratio ξ is defined as the flux of the planet over the flux of the star Fp/Fs
  - It is wavelength dependent
- When we do photometry, we are measuring a weighted average of the flux ratio
- The working definition of this average flux ratio is:
  - $\tau_f(\lambda)$ is the band filter function, and selects the band
  - $\tau_p(\lambda)$is the conversion from flux to electrons at detector
    - as we will see, this is more than a throughput and includes many factors – for now we can call it a conversion efficiency
- 5% root square mean error (RSME) Calibration Uncertainty Allocation on Fp/Fs for TTR5 (Band 1 photometry)



$$\xi = \frac{\int F_p\, \tau_p\, \tau_f\, d\lambda}{\int F_s\, \tau_p\, \tau_f\, d\lambda}$$

weighted sums!

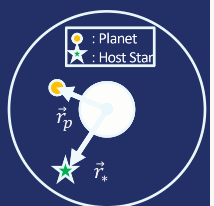


Imaging Calibrations - Synopsis

Star Flux

via placement of star in dark hole and using a calibrated ND filter

also employs a 'ladder' of calibration standard stars

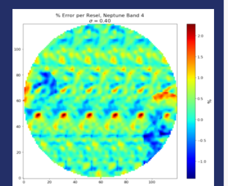


data: on orbit
processing: on ground

Flat Field

use dithered images of Neptune or Uranus

remove common-mode planet features using matched filter

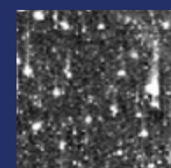


data: on orbit
processing: on ground

Charge Transfer Inefficiency

use trap pumping to identify charge traps

algorithm on ground processes each image for CTI removal

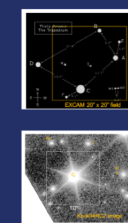


data: on orbit
processing: on ground

Astrometry

Provide absolute astrometric calibration of EXCAM's FOV

geometric astrometric solutions of stellar clusters obs.

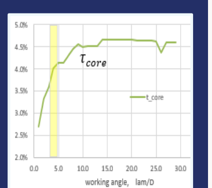


data: on orbit
processing: on ground

Core Throughput

find planet and off-axis star positions in dark hole

raster a photometric standard across the dark hole to measure core throughput vs. field position

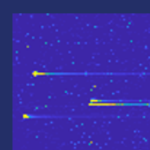


data: on orbit
processing: on ground

Image Corrections

use image data to: remove cosmic ray tails; calibrate EM gain

algorithm for threshold, coincidence corrections

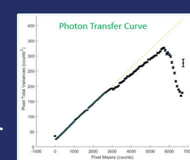


data: on orbit
processing: on ground

Nonlinearity and K gain

image Uranus or Neptune

use photon transfer curve to get detector nonlinearity and conversion gain

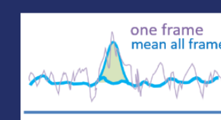


data: on orbit
processing: on ground

Detector Noise Background

Get darks to: remove structure in dark current and CIC

prepare master dark from large number of frames



data: on orbit
processing: on ground

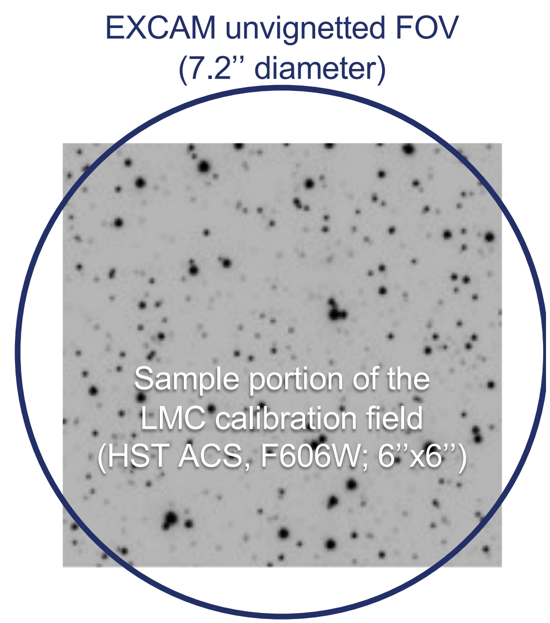
Will continue to add & update as additional input becomes available

Absolute Flux Calibrations

- Periodically observe standard calibrator stars
  - Conducted with color filters with and without the neutral density filters (NDs)
  - 4 white dwarfs, 4 A stars, 4 G stars (e.g., HST CALSPEC and JWST calibrator stars)
    - Exploring simplifying these operations
- ND filters are in the focal plane, requiring calibrations
  - Depositions on NDs will manifest as spatial variations
  - ND filter required to observe unocculted host star
  - Localized, reference ”sweet spot” will be designated/monitored
    - Spitzer/IRAC heritage
  - Will save time by calibrating only a localized position, rather than the entire ND filter

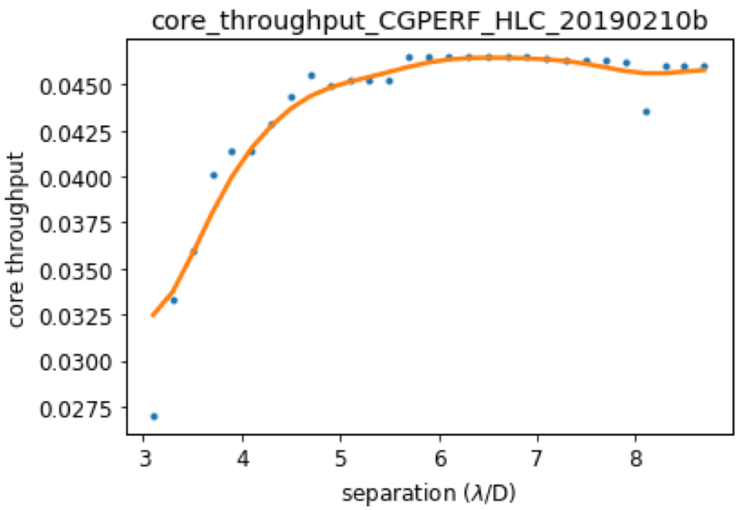
Astrometric Calibrations

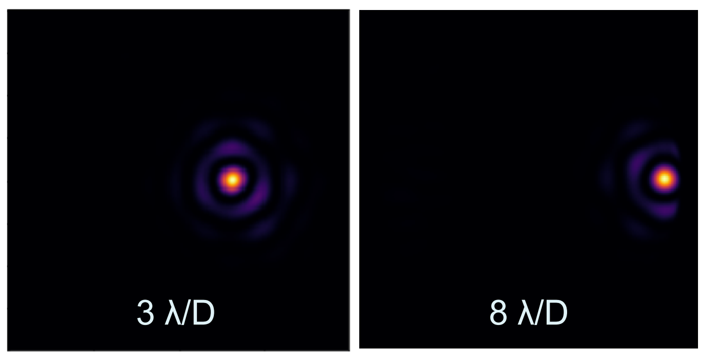
- Observe calibration fields at a number of dither positions, with no coronagraph mask
  - The distortion map calibration fields typically have ~10-100 stars brighter than V~22 pin the unvignetted (7.2 arcsec diameter) field of view per pointing
- HST has established several standard calibration fields mapped to ~1 mas precision, sufficient for CGI
  - 5'x5' region of the Large Magellanic Cloud (in Roman's Continuous Viewing Zone)
  - JWST will observe the same LMC field and additional fields

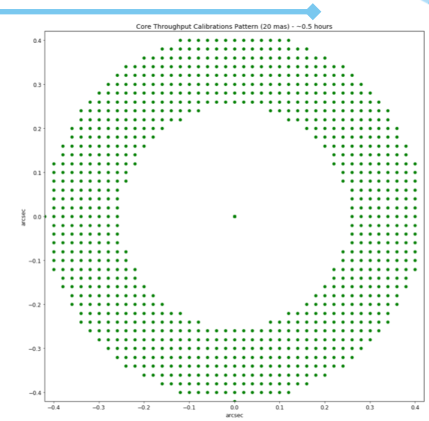


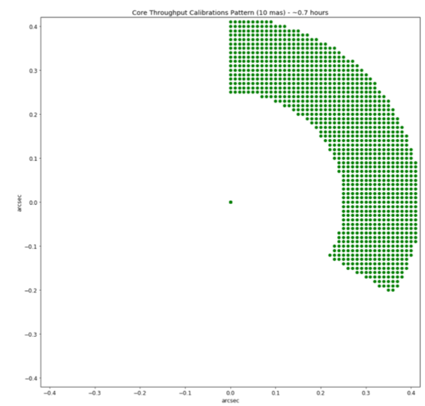
Core Throughput Calibrations

- Measure core throughput and PSF spatial variations by dithering a star across the FOV
  - Sampling patterns are illustrative examples and exact patterns are work to go





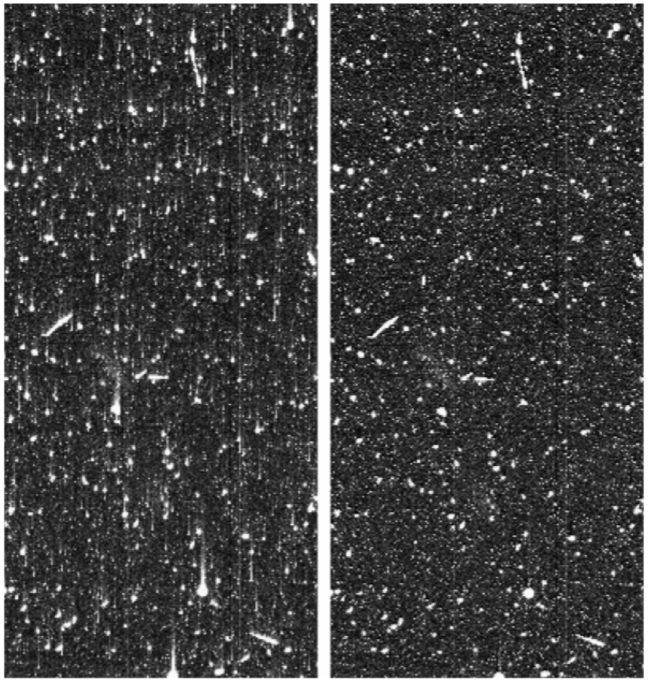




Marie Ygouf (JPL)

Charge Transfer Inefficiency

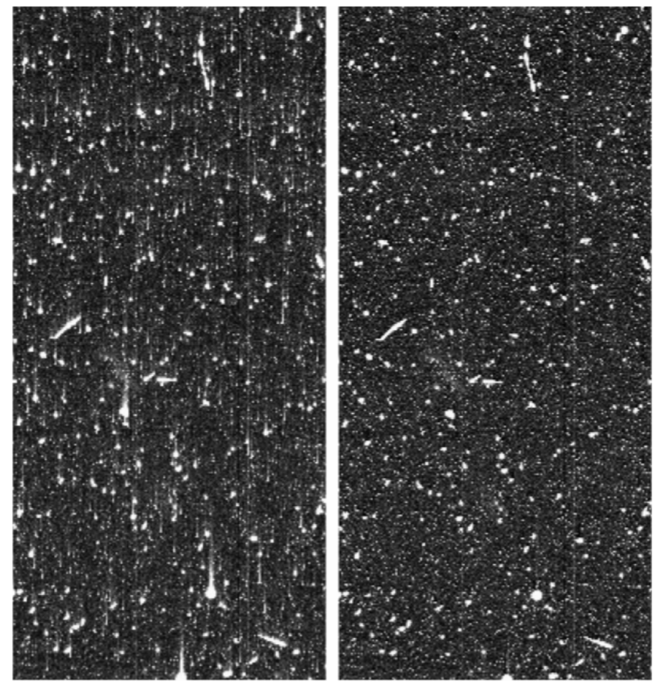
- Charge traps in the pixels temporarily capture and release electrons during parallel and serial readout on their way to the amplifier
  - The traps are caused by radiation damage to the silicon lattice
  - Density of charge traps increases over the mission lifetime of a CCD in a space telescope



Left: HST image with CTI trailing
Right: corrected image

Charge Transfer Inefficiency

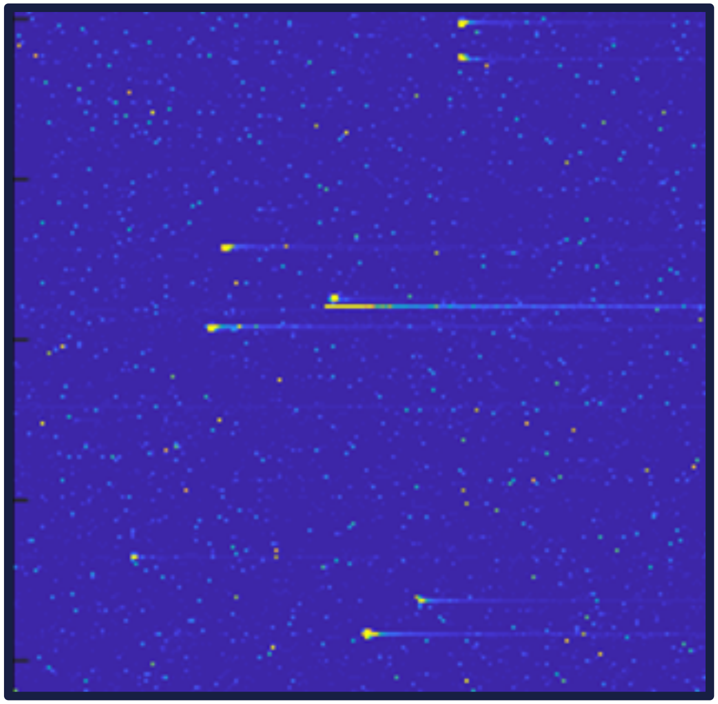
- Trap pumping gives locations, energy levels, and release time constants for each trap species
  - Obtain at sensor temperatures: 170 K (nominal), 190 K, 210 K
- EXCAM will be cooled down only during CGI observations. Some fraction of traps will anneal during warm up – changes trap landscape
  - Need to do trap pumping just prior to cool-down and just after warm-up to track changing trap densities
- Obtain darks just before or after each trap pumping sequence
  - Warm pixels in dark frames leave trails that are used to independently determine release time constants and densities
- ArCTIC Python code is a possible CTI corrector, but has not been tested adequately with photon counted images, and may need modifications



Left: HST image with CTI trailing
Right: corrected image

Cosmic Rays

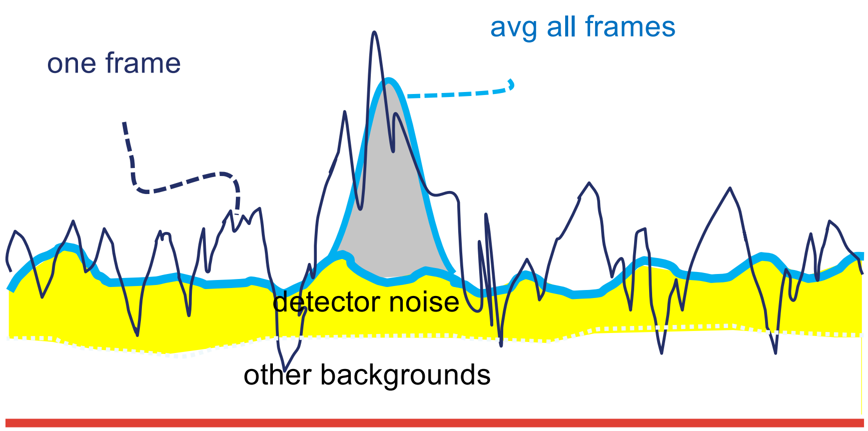
- Our baseline is to simply flag the entire cosmic ray impact and mask each out
- Considering correcting for cosmic ray hits to recover underlying data



Ground EMCCD test data showing muon cosmic rays against a backdrop of dark current (Nathan Bush – JPL)

Darks & Clock Induced Charge

- Darks and Clock Induced Charge will be calibrated by taking many dark frames
- To save Coronagraph overhead, darks will be collected during WFI primary operations



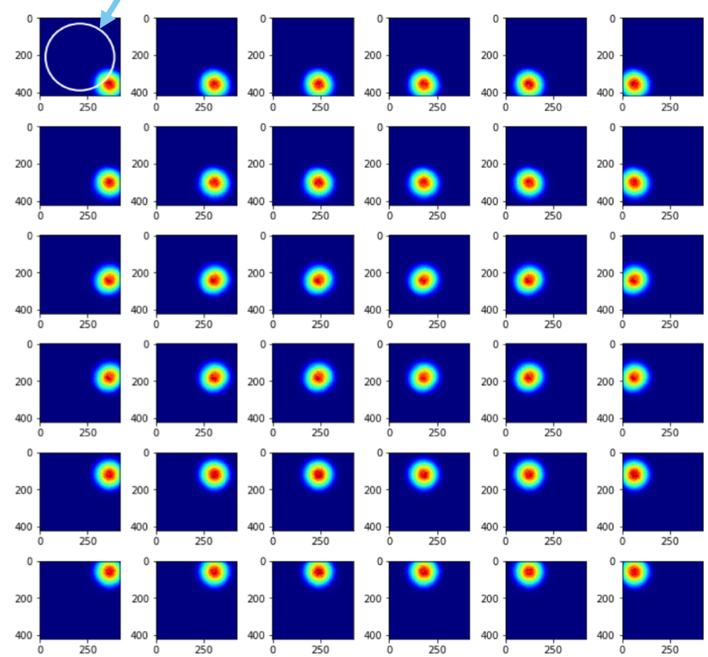
Bijan Nemati (U Alabama – Huntsville)

Flat Fields

- To correct for variations at three spatial scales:
  - Low - e.g., vignetting
  - Medium – e.g., Hubble “measles”
  - High – e.g., pixel-to-pixel variations

Flat Fields

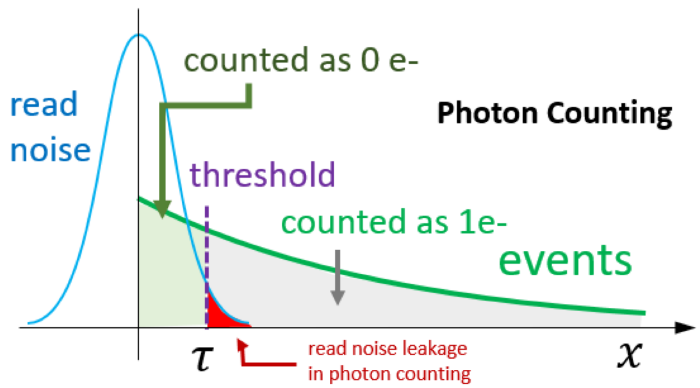
- No flat lamp, so astrophysical source needed
- No non-sidereal tracking, so flat field source will be "ambushed"
- Flat source will be dithered around focal plane between exposures
  - A single flat field (for a single observing mode), takes ~30 minutes
- Fine steering mirror (FSM) raster during an exposure to flatten source
  - Note: CGI only has ~3 slots available on its onboard memory for raster patterns
- Matched filter to divide shared flat source, leaving residuals, which are the flat field measurements for that epoch



Erin Maier (U Arizona – Steward Observatory)

Image Corrections

- Photon counting results in two error sources:
  - Thresholding loss occurs when we record zero electrons when there actually was 1 (or more) image electrons
  - Coincidence loss occurs when we record 1 electron, but there were in fact multiple electrons in the image pixel
- See Nemati 2020 (SPIE) and "Observing Scenario 9 Post-Processing report"[1] by Ygouf et al. (2021) for more details

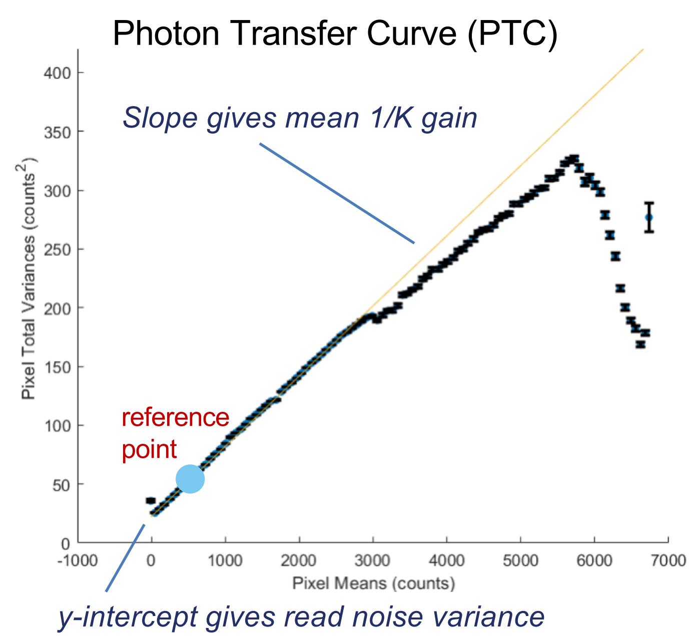


Bijan Nemati (U Alabama – Huntsville)

[1] https://wfirst.ipac.caltech.edu/sims/Coronagraph_public_images.html#CGI_OS9_report

Nonlinearity and K gain

- To correct for non-linear pixel responses and determine the mean K gain, the conversion factor between electrons and average counts for a given EM gain value
- Apply PTC "differencing + stacking" analysis method
  - This method forms differences from pairs of frames in same exposure set and then stacks them to form a datacube.
  - Calculate variance for each pixel in the datacube



Nathan Bush (JPL),
Guillermo Gonzalez (U. Alabama – Huntsville),
Bijan Nemati (U. Alabama – Huntsville)

Polarimetry Calibrations

- Polarization standards are observed to estimate and correct for instrument polarization effects
  - These instrument polarization effects are described by the end-to-end optical system Mueller Matrix (MM)
    - Critical assumption: instrumental polarization is field-invariant
  - MM coefficients will be measured on the sky by observing a minimum of 3 polarization calibrators
    - 1 unpolarized standard
    - 2 polarized standards with precisely-known linear polarization fractions and orientations, as provided by ancillary polarimetry data
    - Identifying specific calibrators needs to be done
- Polarimetric flat fields will also be collected

Spectroscopic Calibrations

- Spectral dispersion scale and orientation
  - Observe an unocculted star and cycling through the sub-band/narrowband filters
- Wavelength zero-point
  - Apply narrowband DM satellite spots to the expected planet offset, while the reference star is occulted
- Slit loss and the line spread function
  - Observe an unocculted star over a grid of PSF-to-slit alignments

Thank you!

Any questions?