H4RG-15 detector features, performance statistics, and characterization data products for VLT-MOONS

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ESO Detector Systems Group

VLT MOONS

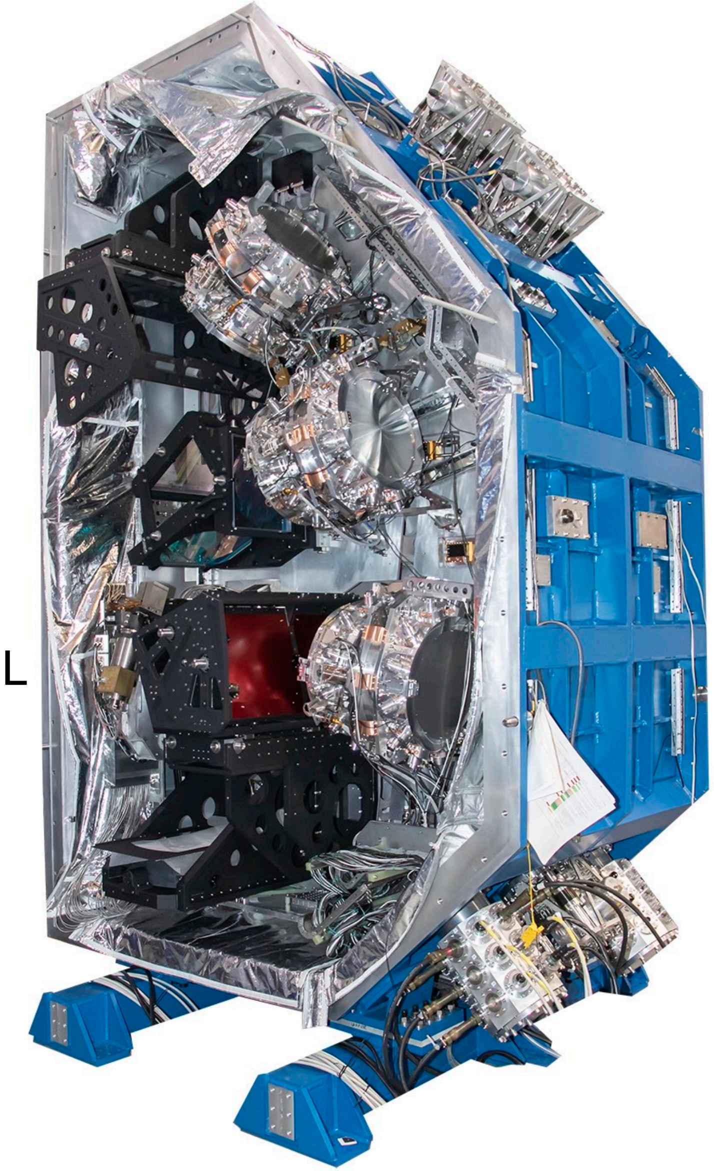
Data Classification: PUBLIC

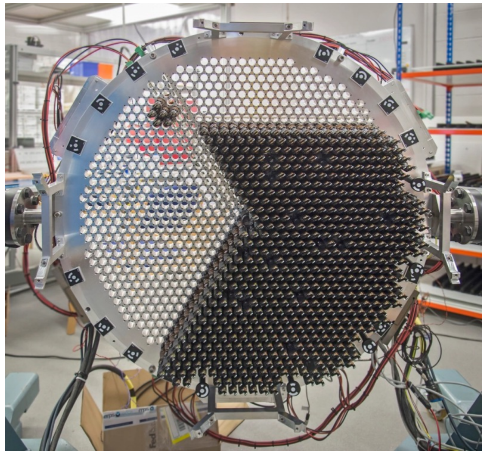
VLT-MOONS instrument

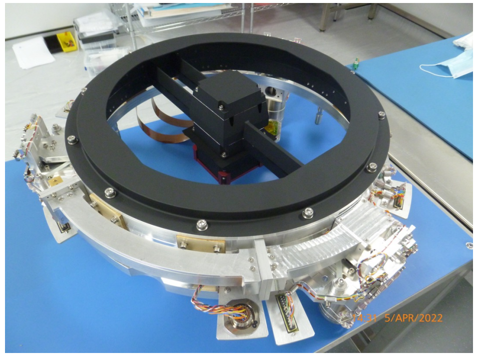
- Fibre fed Multi-object Spectrograph mounted on VLT Nasmyth
- +1000 fibre deployable over 500 sq. arcmin
- Wavelength 0.6 to 1.8 um, with low- and high-resolution modes (R = 4-20k)
- f/0.95 Schmidt Cameras
- 4x H4RG-15 Teledyne (YJ and H bands) and 2x LBNL Fully Depleted CCDs (RI bands)

Science Goals (examples):

- galaxy formation and evolution near peak of star formation (z = 0.8-3)
- Resolved stellar populations (Gaia follow-up): radial velocities, metallicities and chemical abundances



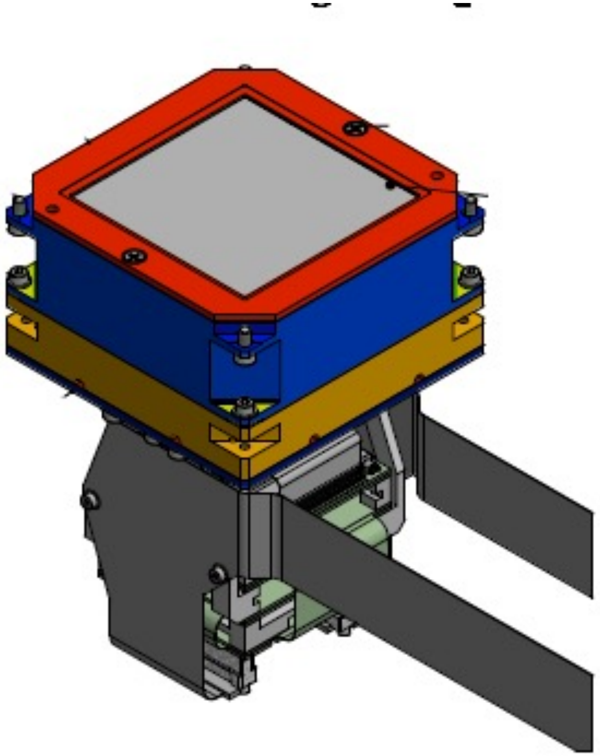


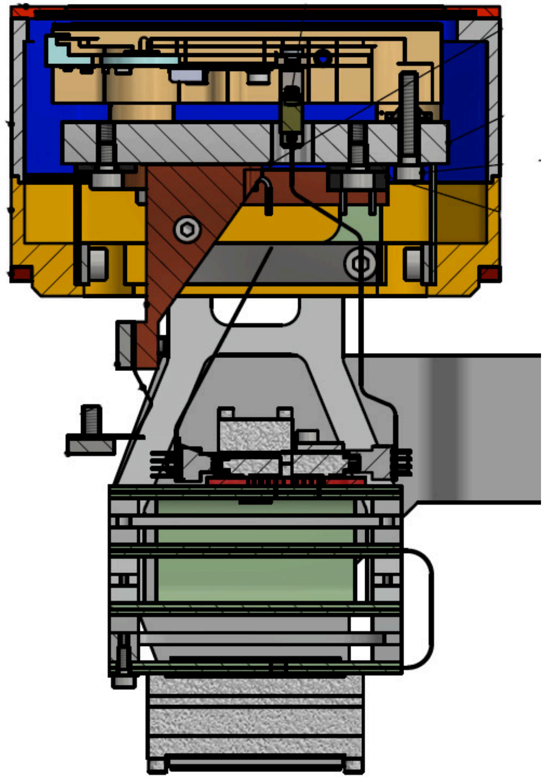


https://vltmoons.org

MOONS Detector Systems

Detectors must fit inside central obscuration of Schmidt camera. → Compact cold electronics design. Operated with ESO's warm NGC controller. (H4RG-15 design pictured)





See: *Alvarez et al. AN Oct. 2023*
https://doi.org/10.1002/asna.20230064

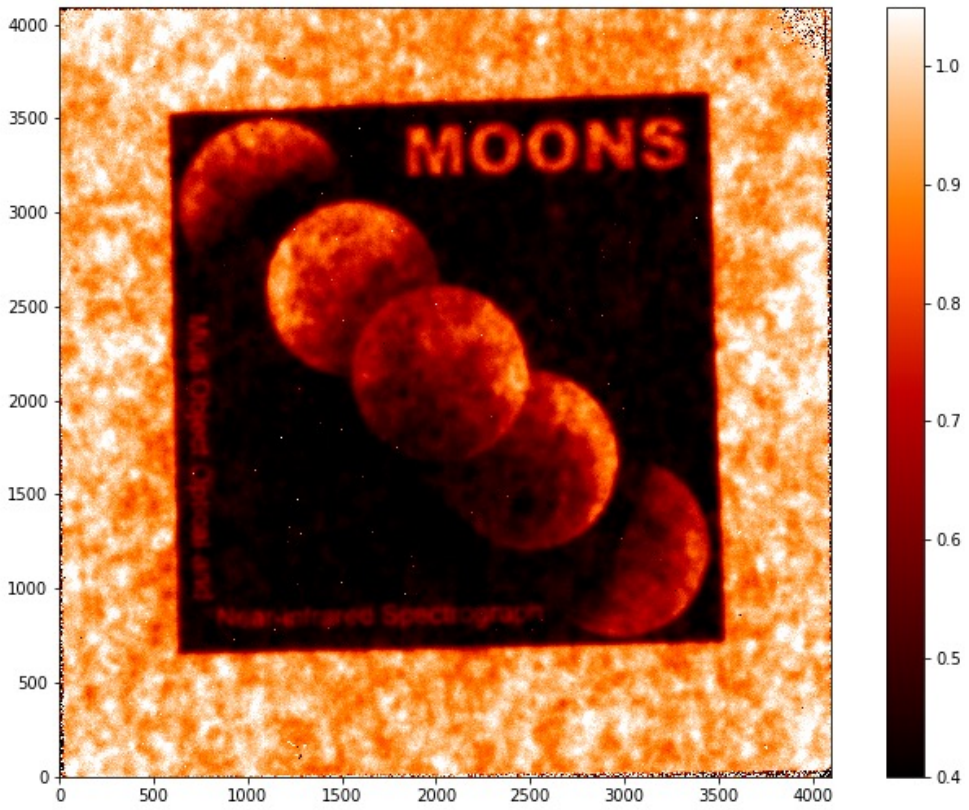
MOONS H4RG-15 performance

MOONS H4RG-15 characterization program

- 5x H4RG-15s characterized (1 engineering grade, 4 science grade)
- Full characterization plan with defined parameters, datasets, analysis methods, and data products.
- Identical datasets acquired on all devices, over a range of operation temperatures
  - default 40K, some measurements made up to 85K to inform future instruments
- (Nearly) fully automated data acquisition and analysis.

H4RG-15: ENG-20370

Pinhole image of MOONS logo



Data Classification: PUBLIC

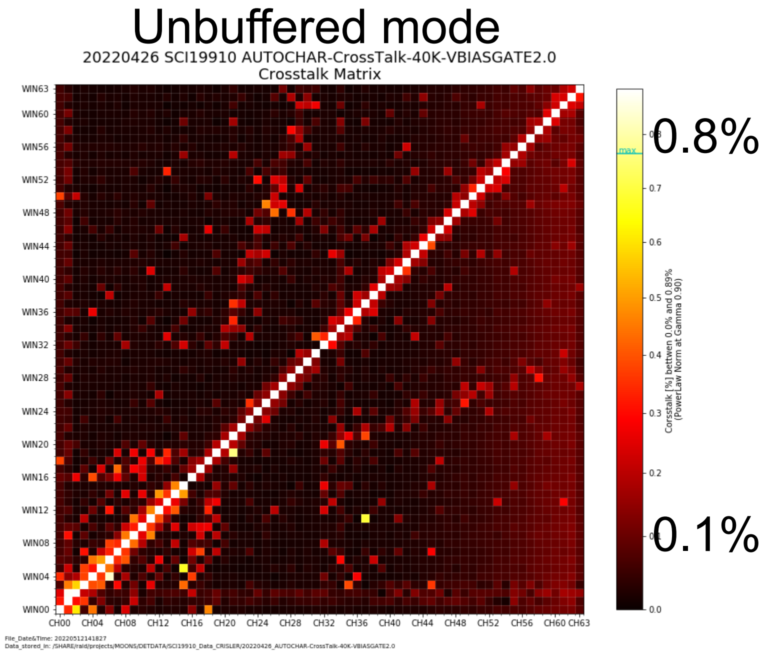
H4RG-15 Operation parameters

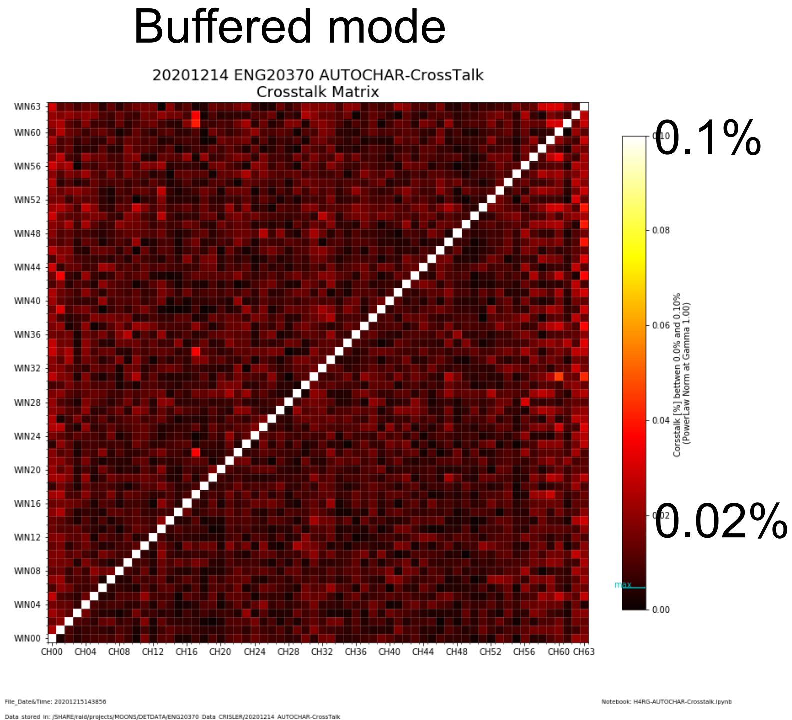
- MOONS is a spectrograph which primarily uses long readouts and requires low noise.
- 40K operating temperature decided upon primarily due to:
  - Lower dark current/less hot pixels
  - Lower persistence
- Buffered mode operation selected primarily to:
  - Allow more reads in shorter exposures (lower noise in UTR frames).
  - Reduce channel-to-channel crosstalk that would cause contamination due to bright sky lines.

Crosstalk matrix

- Amplifier crosstalk greatly reduced by switching to buffered mode operation, < 0.01% coupling.
- No ghosts from bright sources.
- Primary reason why MOONS decided to use buffered mode despite the additional buffer glow – did not want to be correcting crosstalk contamination from skylines in software!

See: George et al. JATIS Nov. 2019
https://doi.org/10.1117/1.JATIS.6.1.011003

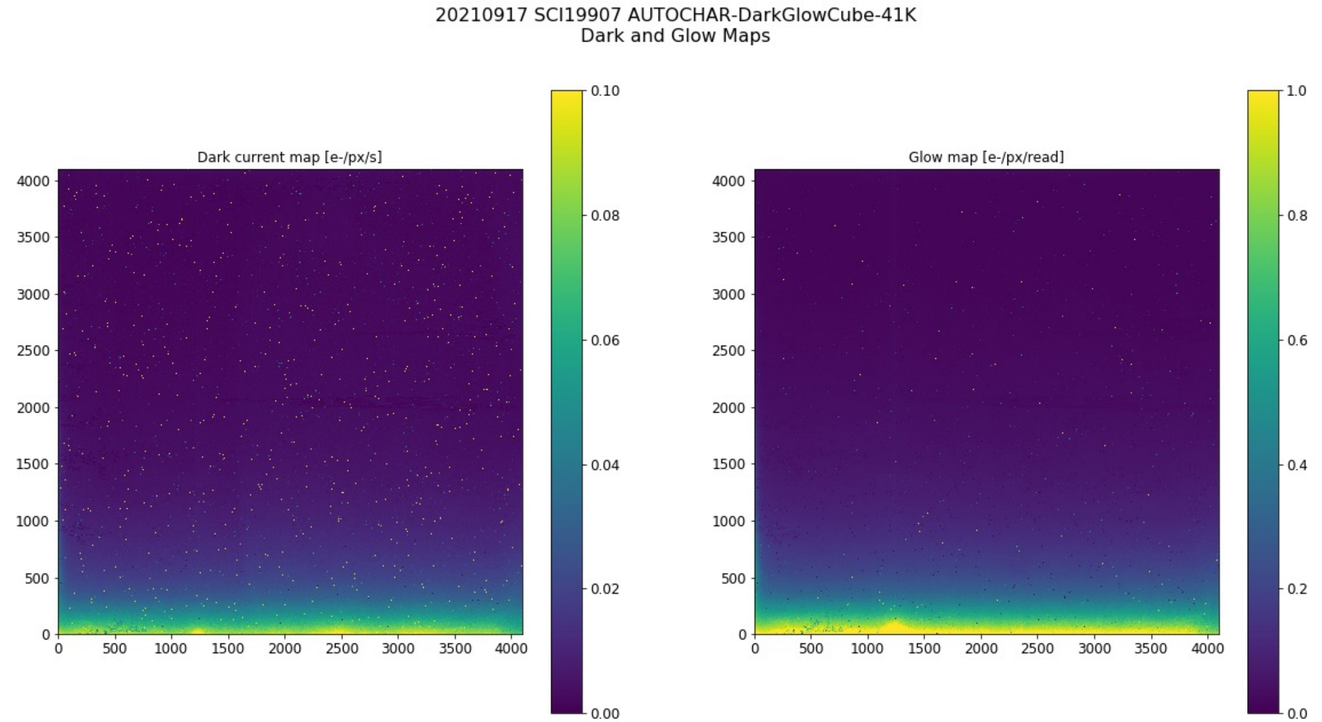




Data Classification: PUBLIC

Dark Current and Glow per Read

- Generally good performance, except glow from output buffer (glow-per-read and glow-per-time component)
- In MOONS, Filter directly in front of detector means that any glow from PEDs will be reflected back onto detector!



SCI-19907 No filter installed

File_Date&Time: 20210921191211
Data stored in: /SHARE/raid/projects/MOONS/DETDATA/SCI19907 Data CRISLER/20210917 AUTOCHAR-DarkGlowCube-41K

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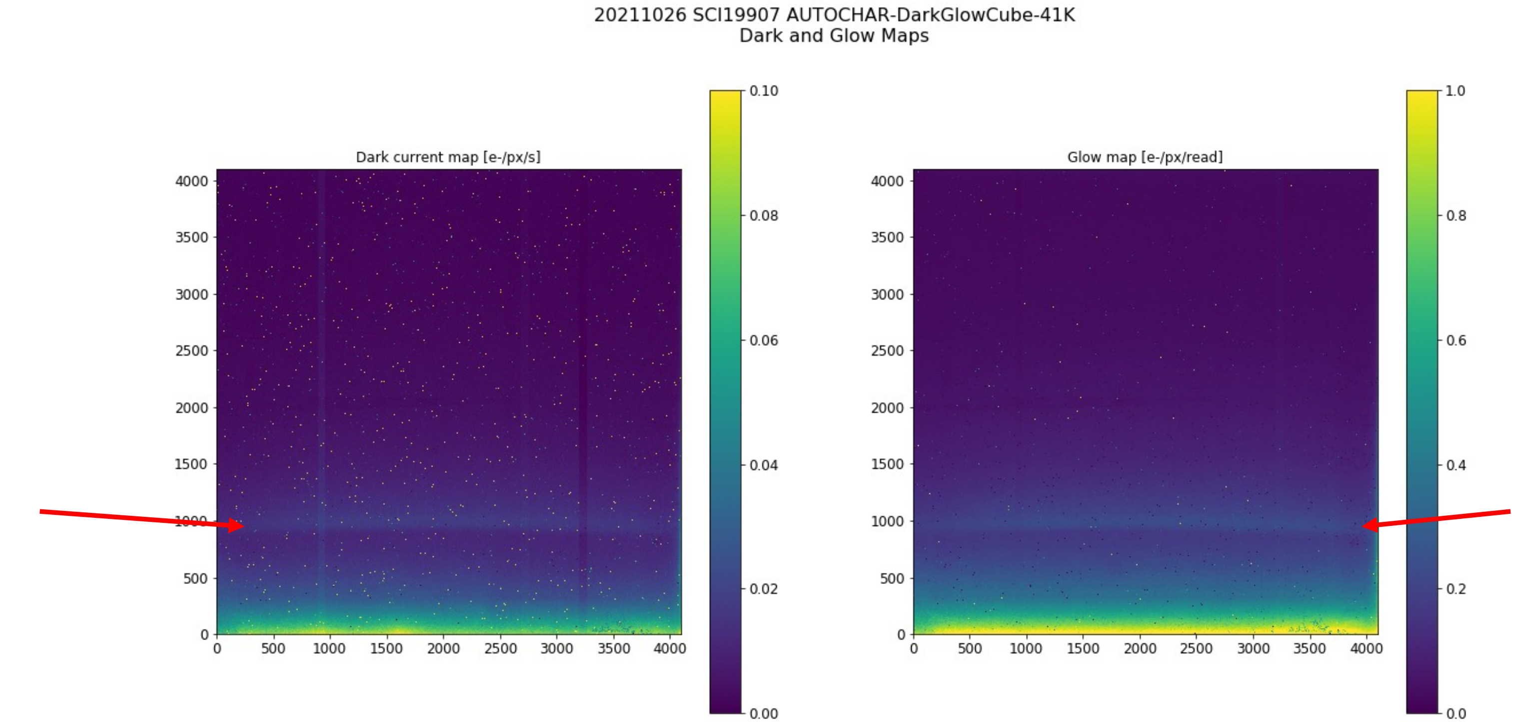


SCI-19907 Filter installed

File_Date&Time: 20211027153350
Data stored in: /SHARE/raid/projects/MOONS/DETDATA/SCI19907 Data CRISLER/20211026 AUTOCHAR-DarkGlowCube-41K

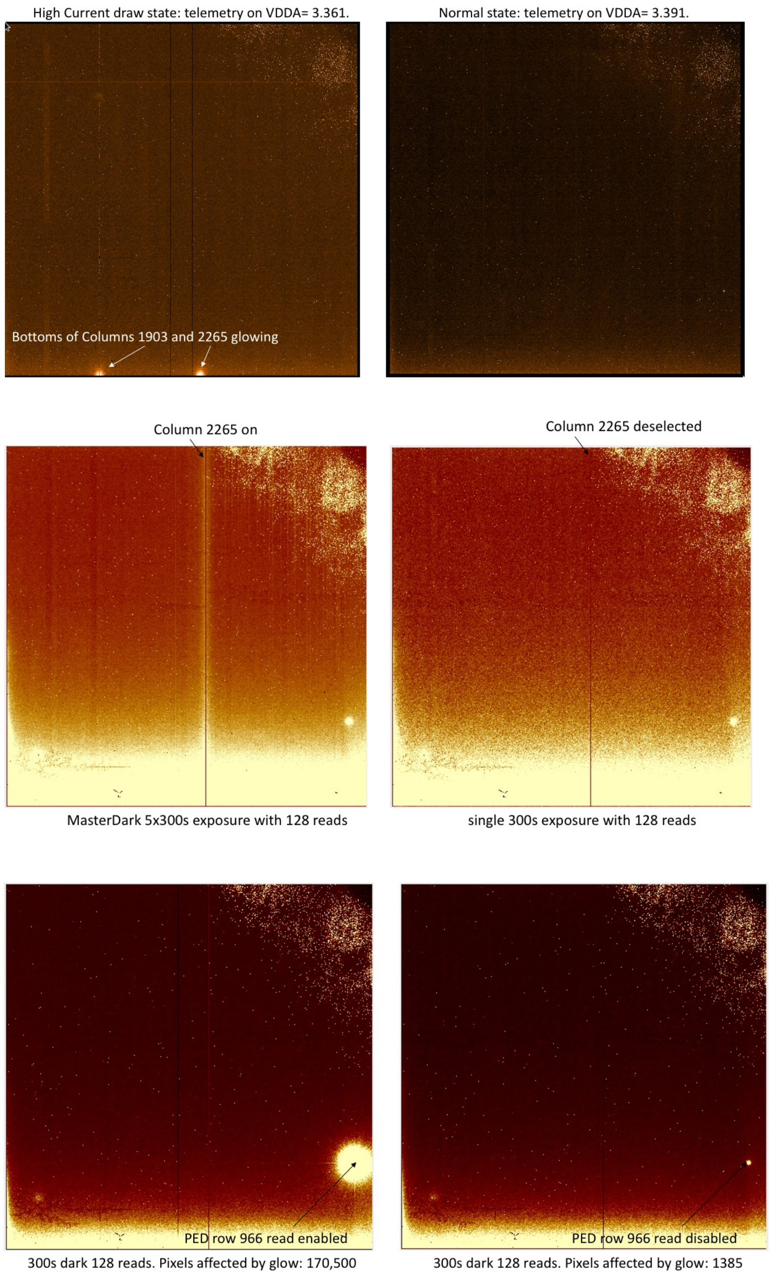
Data Classification: PUBLIC

Dark Current and Glow per Read

- Hot pixel regions were reduced a lot in some detectors by going to a 40K operating temperature (despite a 2.5 μm cutoff wavelength). Some detectors had nearly no hot pixel regions however.
- Characterization of the output buffer glow were reported at SDW 2022 in Bezawada et al. See also upcoming paper on detector operation strategies for how to reduce this glow.
- In MOONS, worst case of glow is at the bottom of the array where the glow can reach 1-2 e-/px/read.
- Good news is that this characterization program spurred the development of v2 of the H4RG-15 ROIC—which seems to have fixed this glow issue!

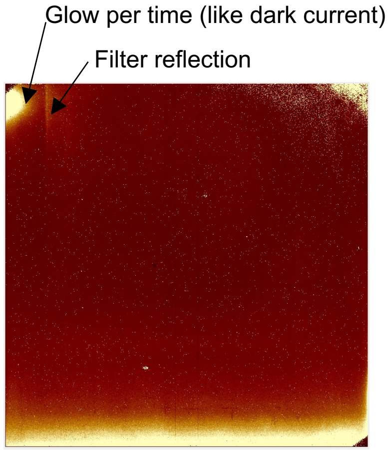
Cosmetics and PEDs

- Generally very good operability, but some detectors had PEDs.
- Different types of PEDS we encountered
  - Glowing columns when column deselect fails (fix by disabling and re-enabling column deselect) → fixed in v2 ROIC.
  - PED that reacts as a glow per read (fix by skipping rows).
  - PED that reacts as dark current (sometimes but not always fix by deselecting column where PED is located).



ENG-20370

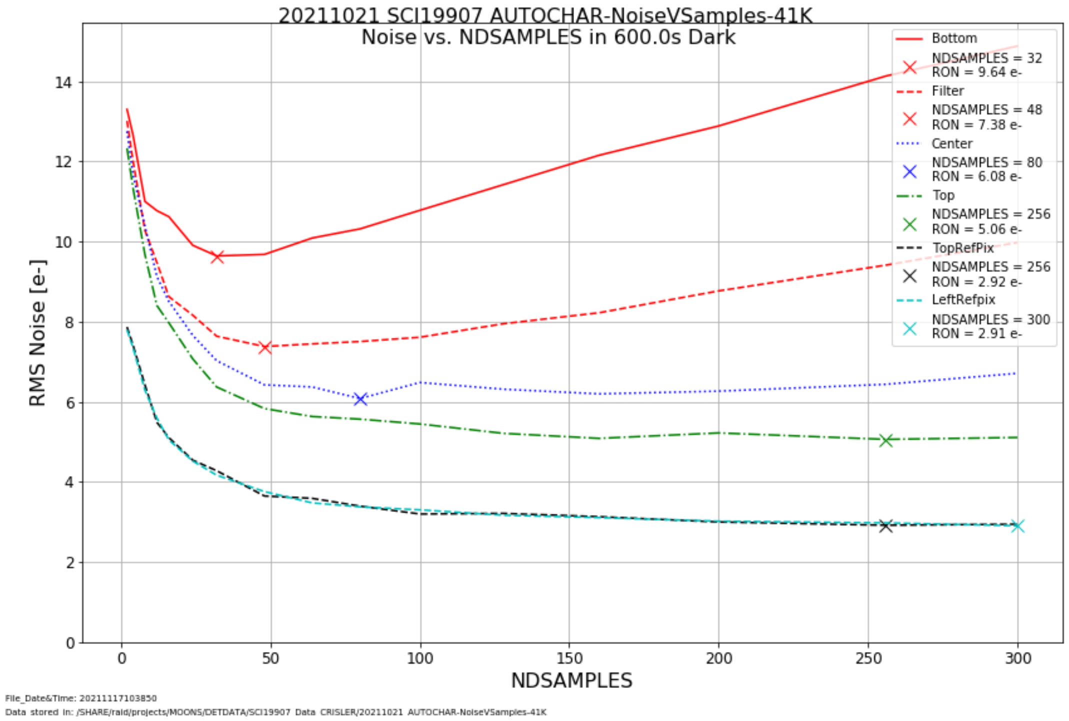
Dark images (arbitrary scaling) from ENG-20370 and SCI-20372 detectors illustrating different types of PEDs we encountered

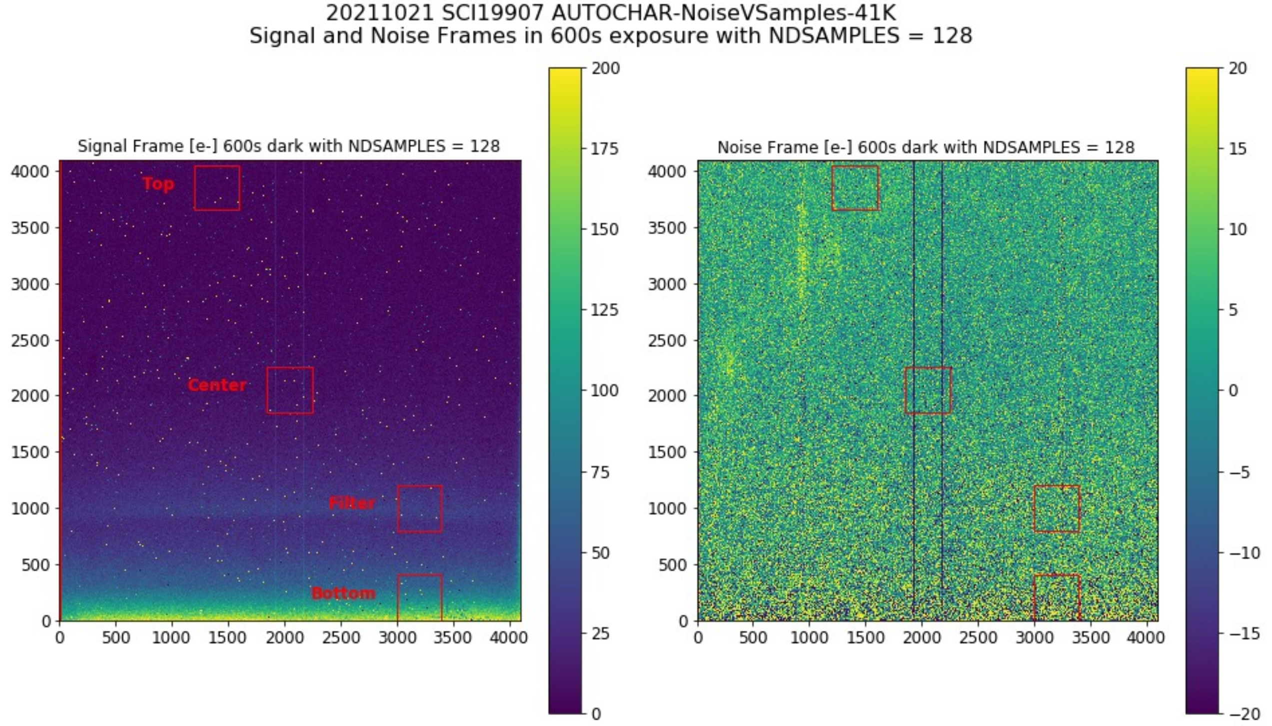


SCI-20372

Noise vs. Samples

- Glow from buffer limits noise performance in long exposures at bottom of array.
- In MOONS, we limited the maximum number of samples in UTR to 128 even for long readouts to limit impact on noise performance. Median over array around 5 e- RMS in UTR readouts, up to 11e- at bottom of array.

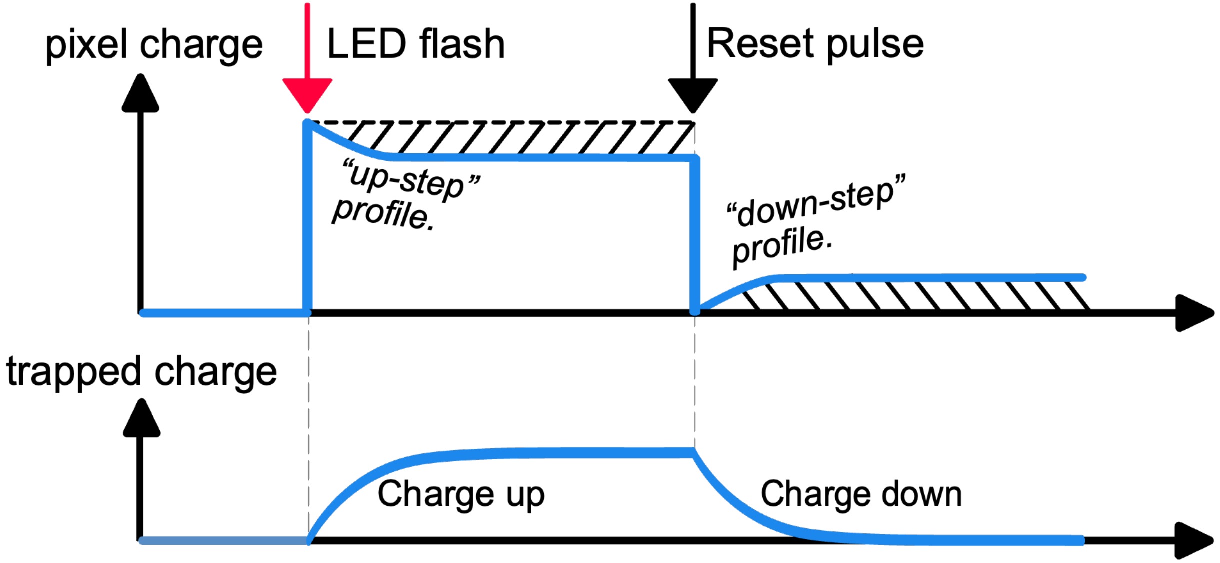


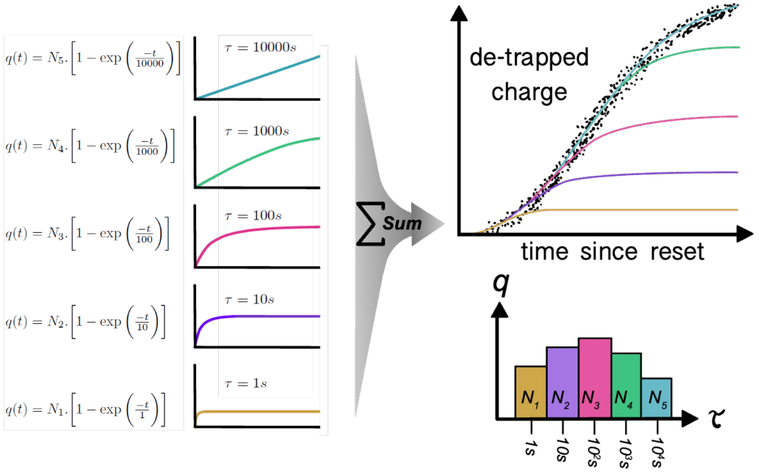


Data Classification: PUBLIC

Persistence

- Measured using special sequence
  - Flash LED
  - Soak Traps
  - Detrap over 14 hours
- Fit using time constant bins
  - Similar to DLTS, but sensitive to much longer time constants.

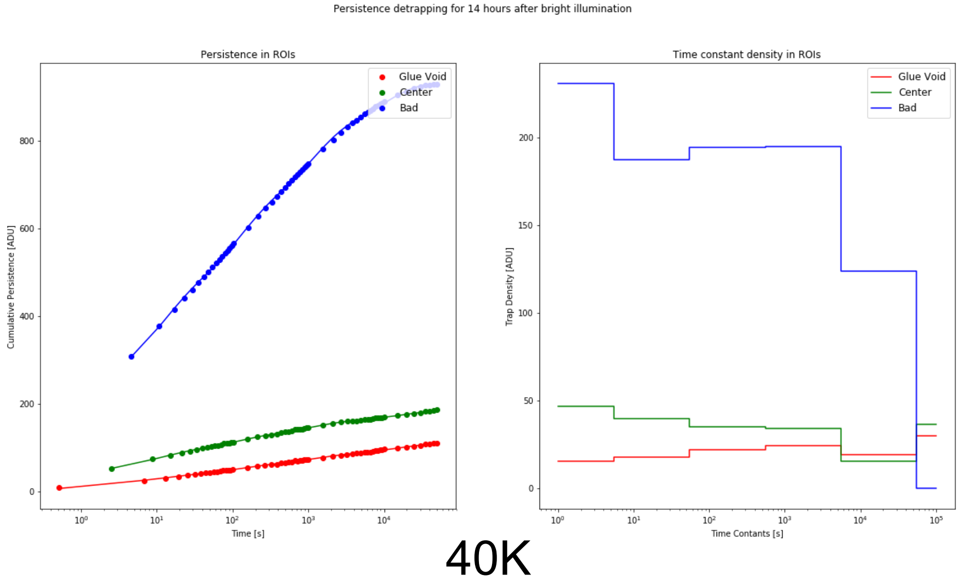


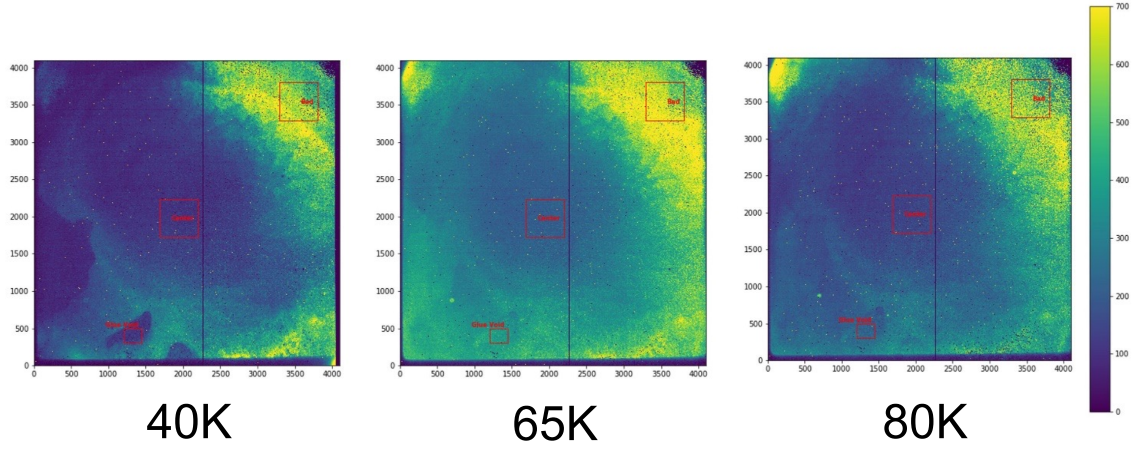


See: Tulloch and George, JATIS 2019
https://doi.org/10.1117/1.JATIS.5.3.036004

Persistence

- Measured persistence from 40-85K
  - Fit model with traps in time constant bins.
  - Trap density in time constant bin changes → measure trap energy.
- Varied from detector to detector by an order of magnitude. (0.2-2.5% trap density)
- Detectors with cross-hatch and more hot pixels at 85K showed higher persistence even at 40K.
- Peak in persistence around 65K
  - Traps faster than frame time at 85K
  - Traps slow (frozen out) below 50K





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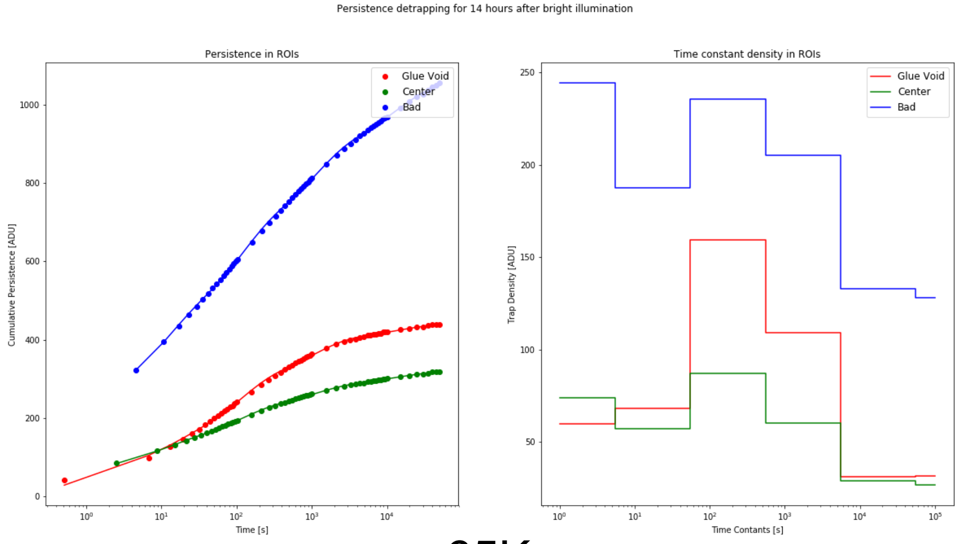
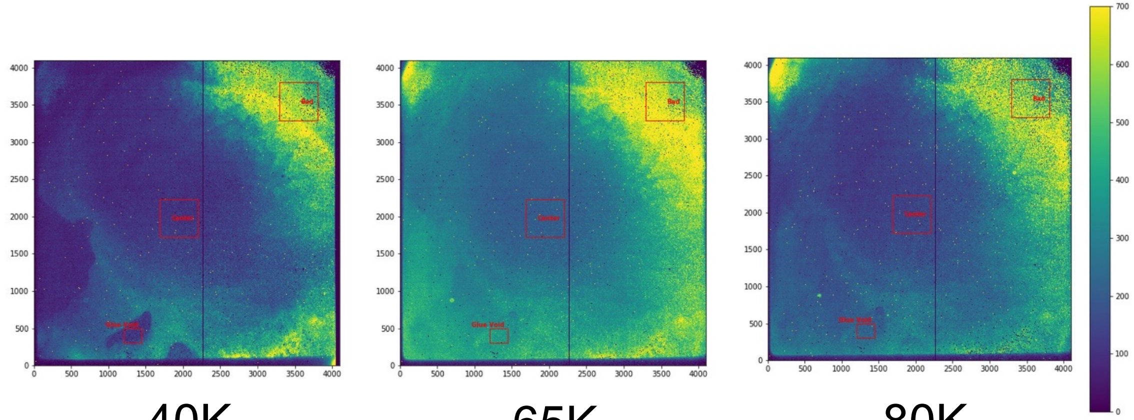


65K



40K

65K

80K

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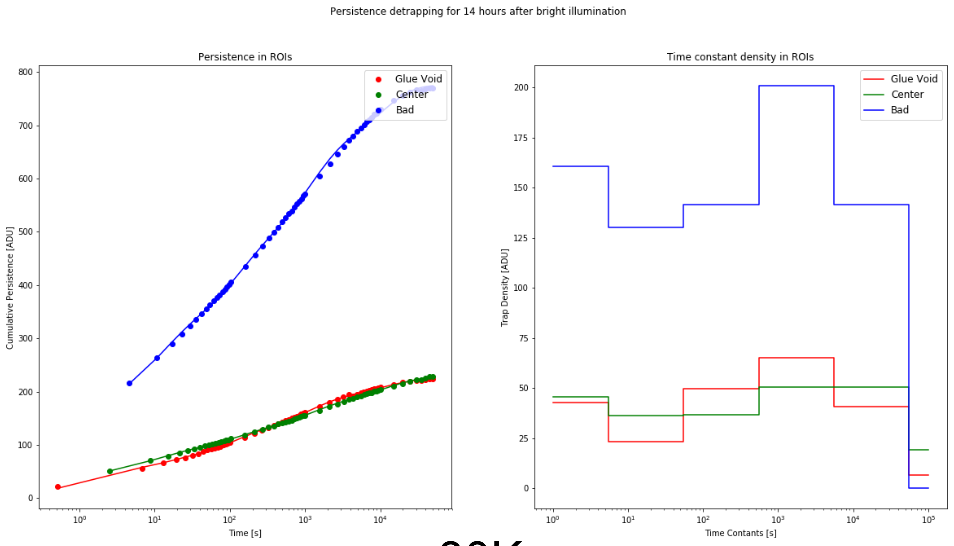
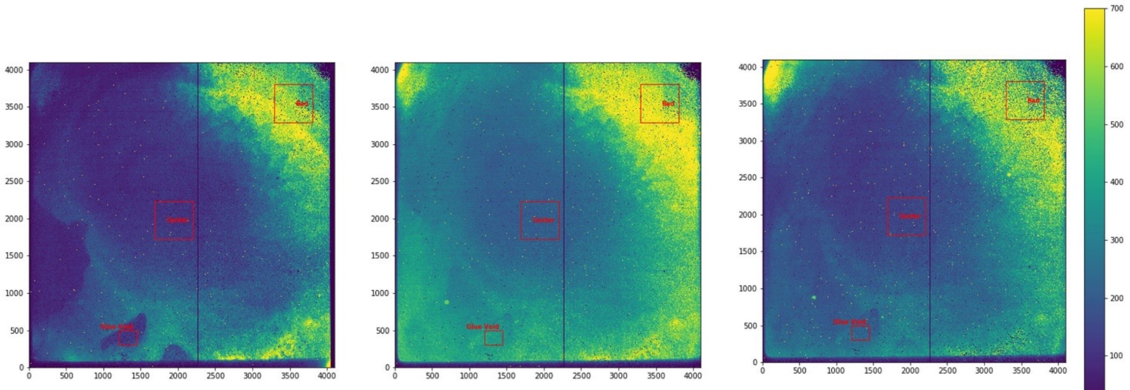


80K



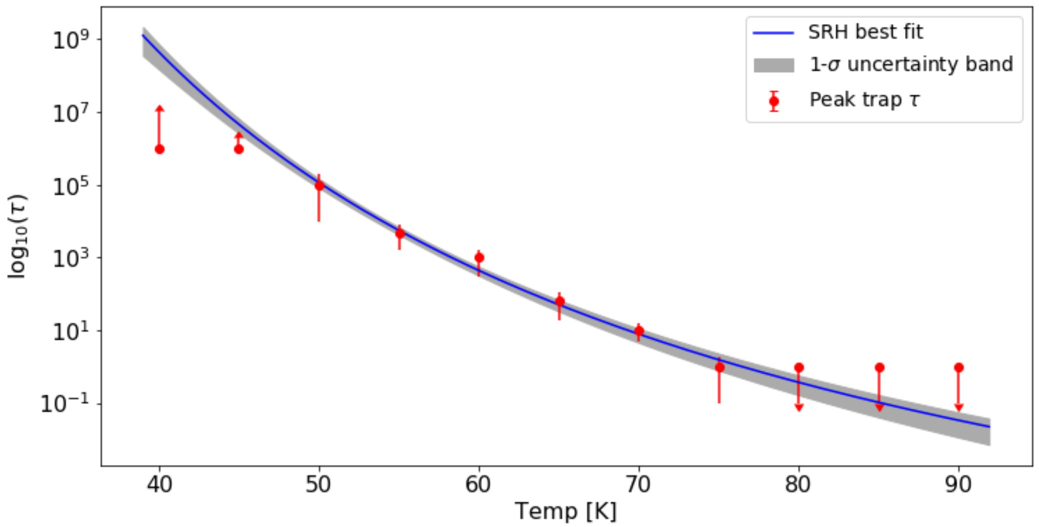
40K 65K 80K

Persistence

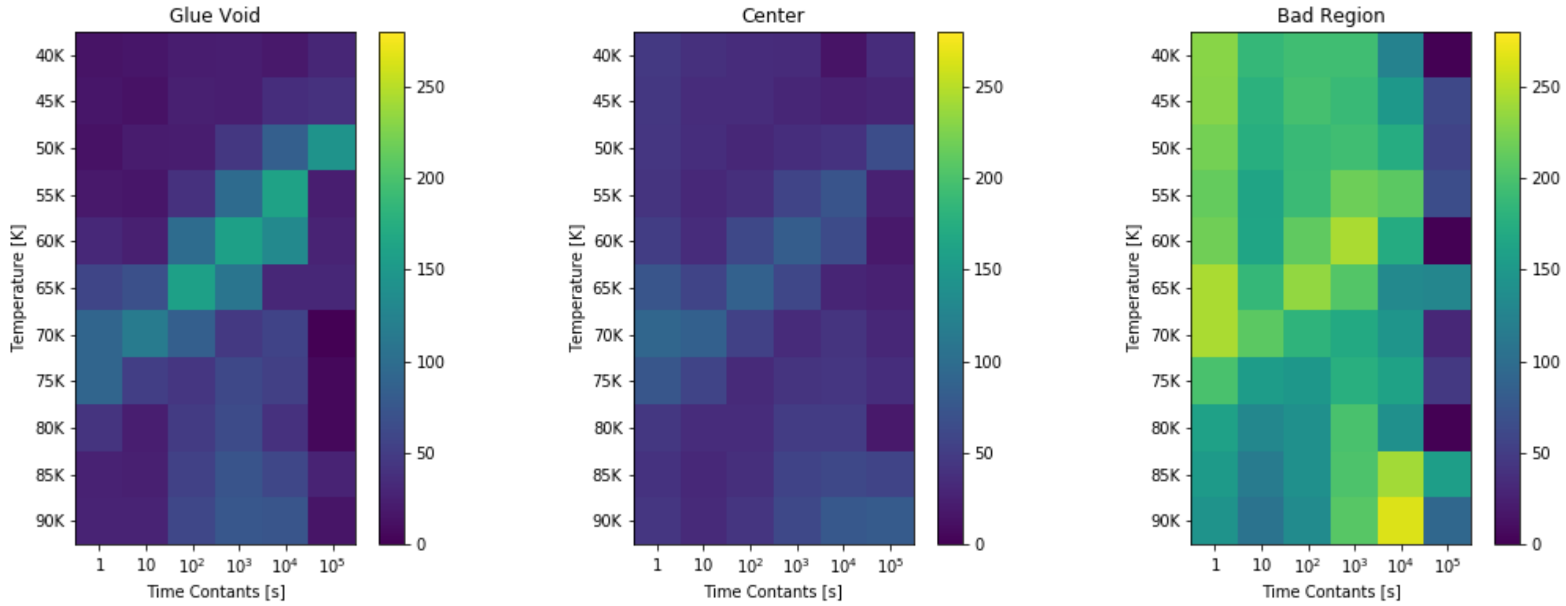
$$\tau_{detrap} = \frac{1}{AT^2} e^{-\frac{E_{trap}}{kT}}$$

$$A = 4\sqrt{6}\ \pi^{3/2} \sigma_{trap} \frac{k^2 m_{eff}}{h^3}$$

$E_{trap} = 0.13\text{eV}$



Persistence detrapping time constant distribution at different temperatures

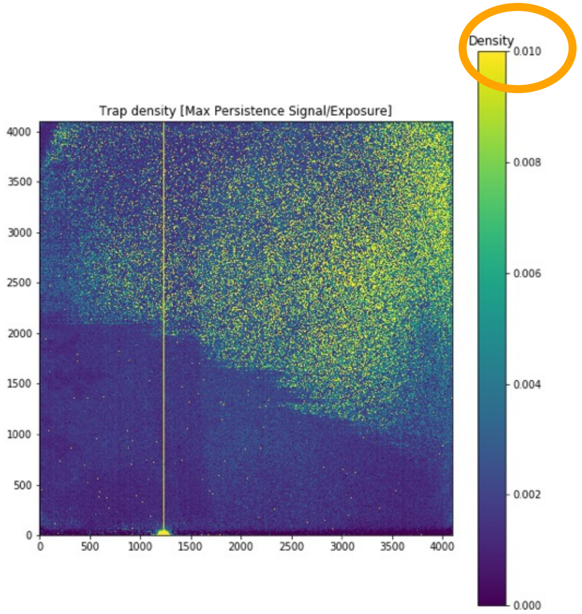


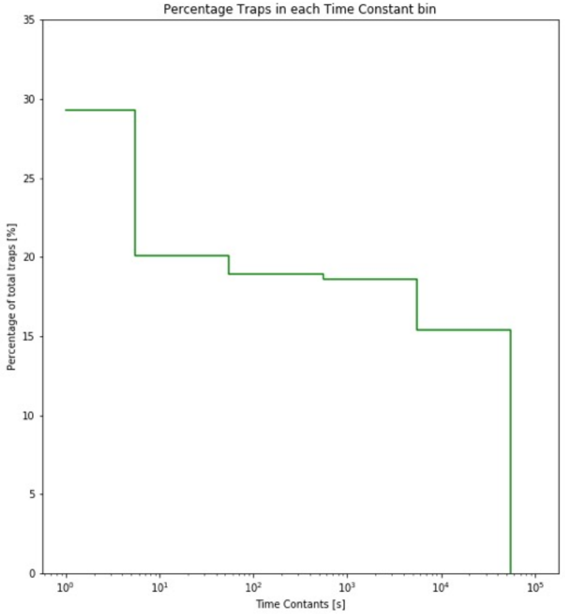
See: Ives et al. SPIE Dec. 2020
https://doi.org/10.1117/12.2562408

Data Classification: PUBLIC

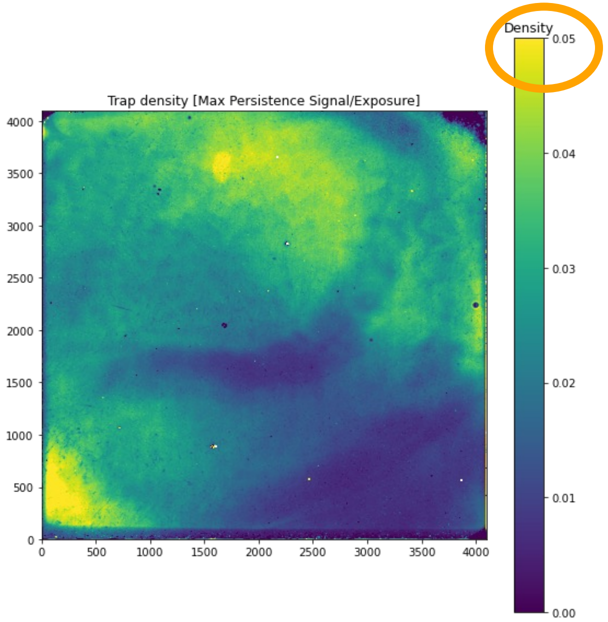
Persistence - comparison

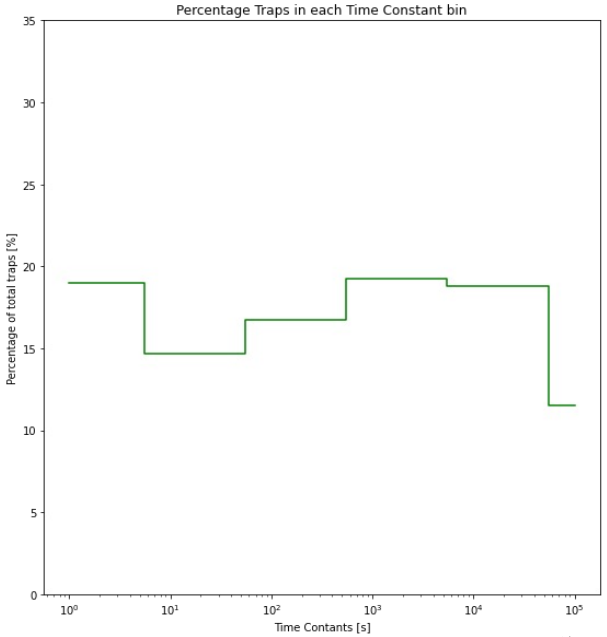
- 0.2% trap density in best detector (SCI-19907)





- 2.5% trap density in worst detector (SCI-20372)



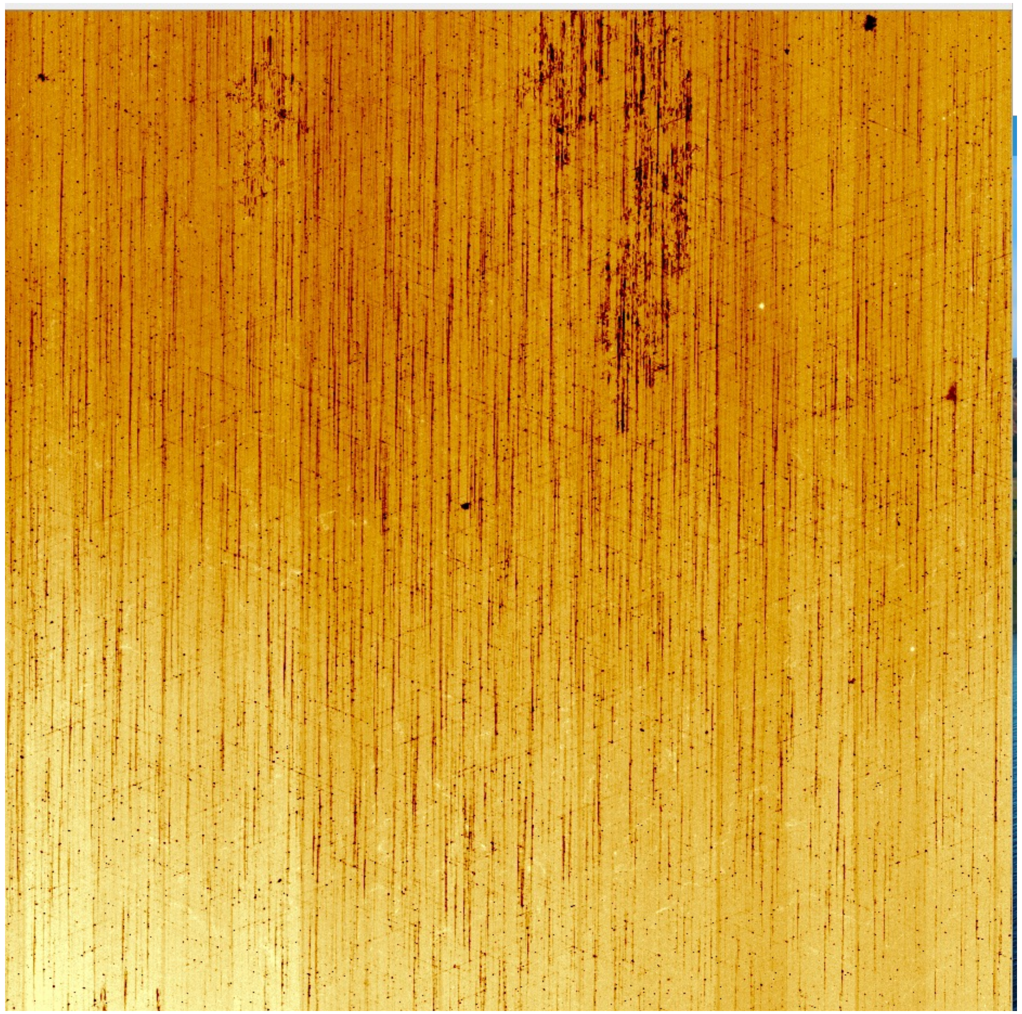


Data Classification: PUBLIC

Crosshatch

- Some devices (SCI-20374 and SCI-20372) showed a crosshatch pattern under illumination
- Indicative of stress in MCT
  - These areas typically had higher dark current and higher persistence.

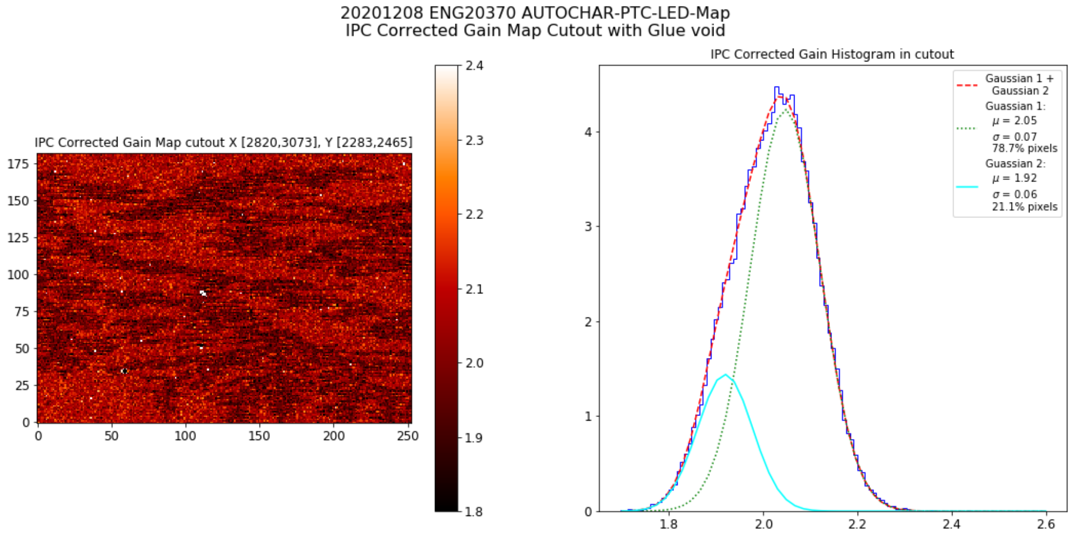
Cross-hatch pattern near center of SCI-20374

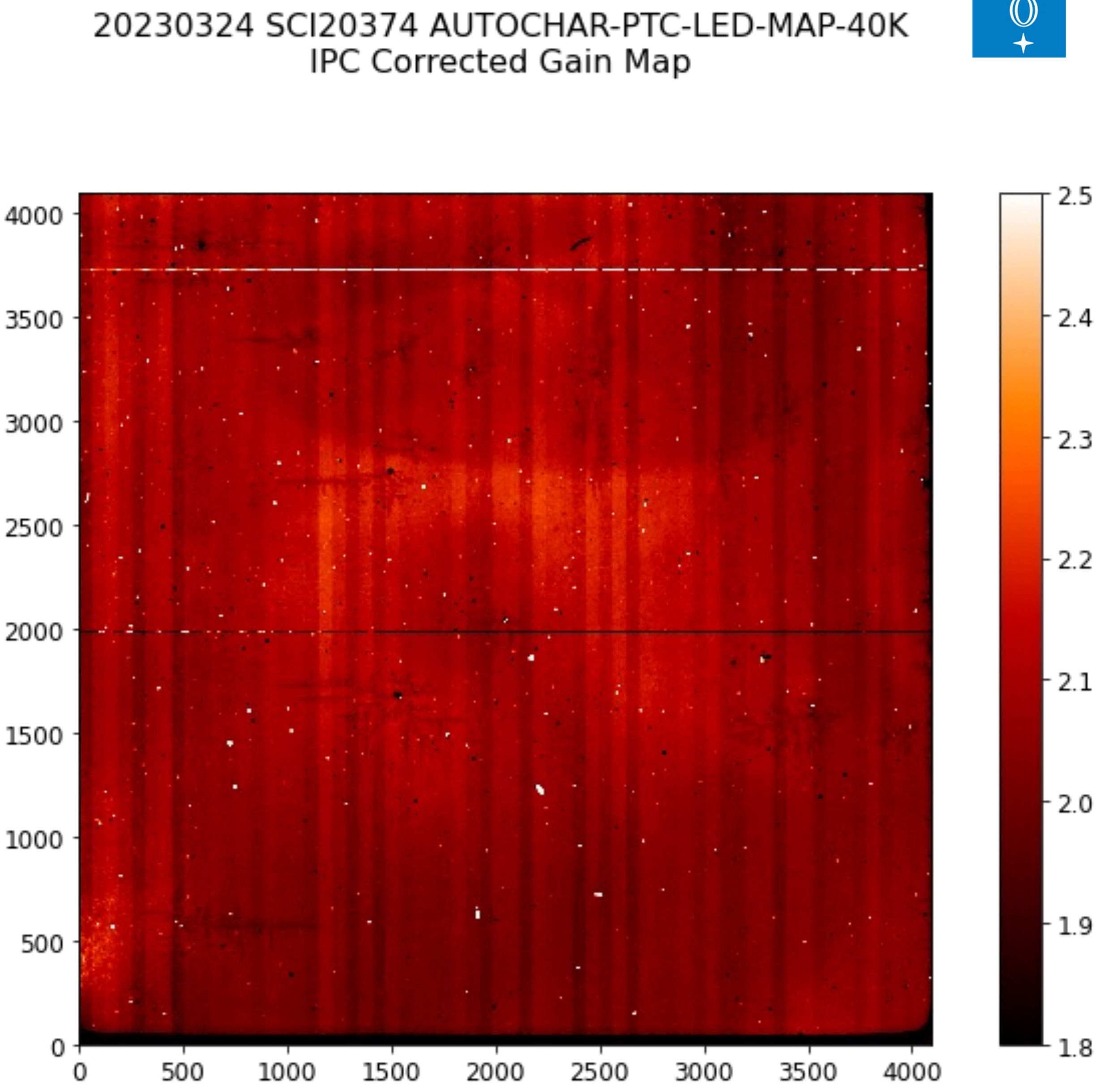


Data Classification: PUBLIC

Gain Map

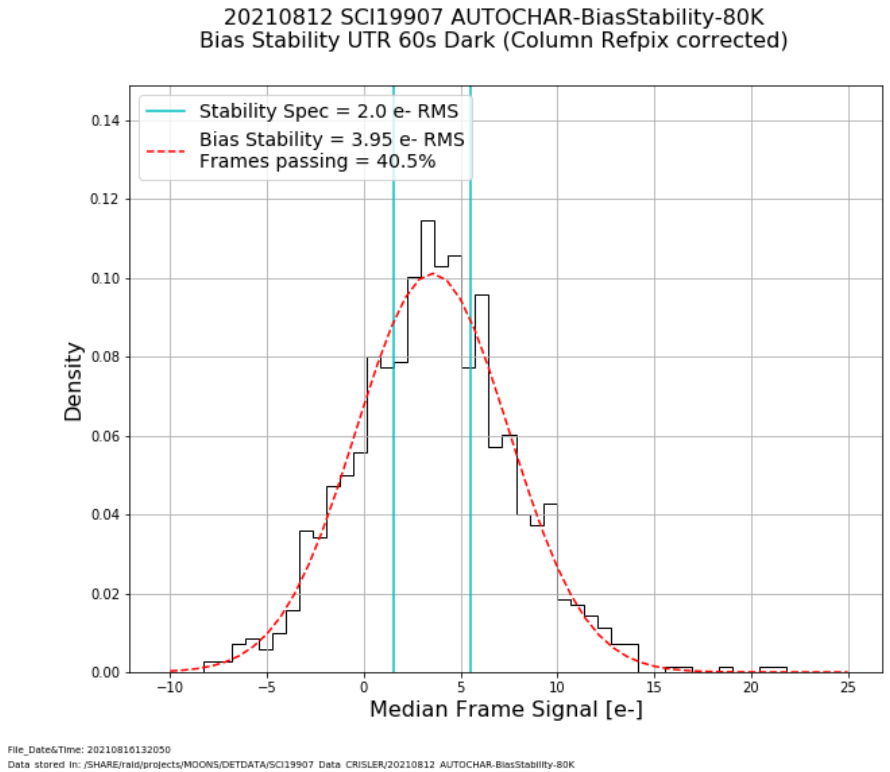
- MOONS uses a median Gain per output in analysis, 64 values per detector saved in fits headers.
- However – much more variation in device! Glue voids (ice crystals) have ~10% lower gain.

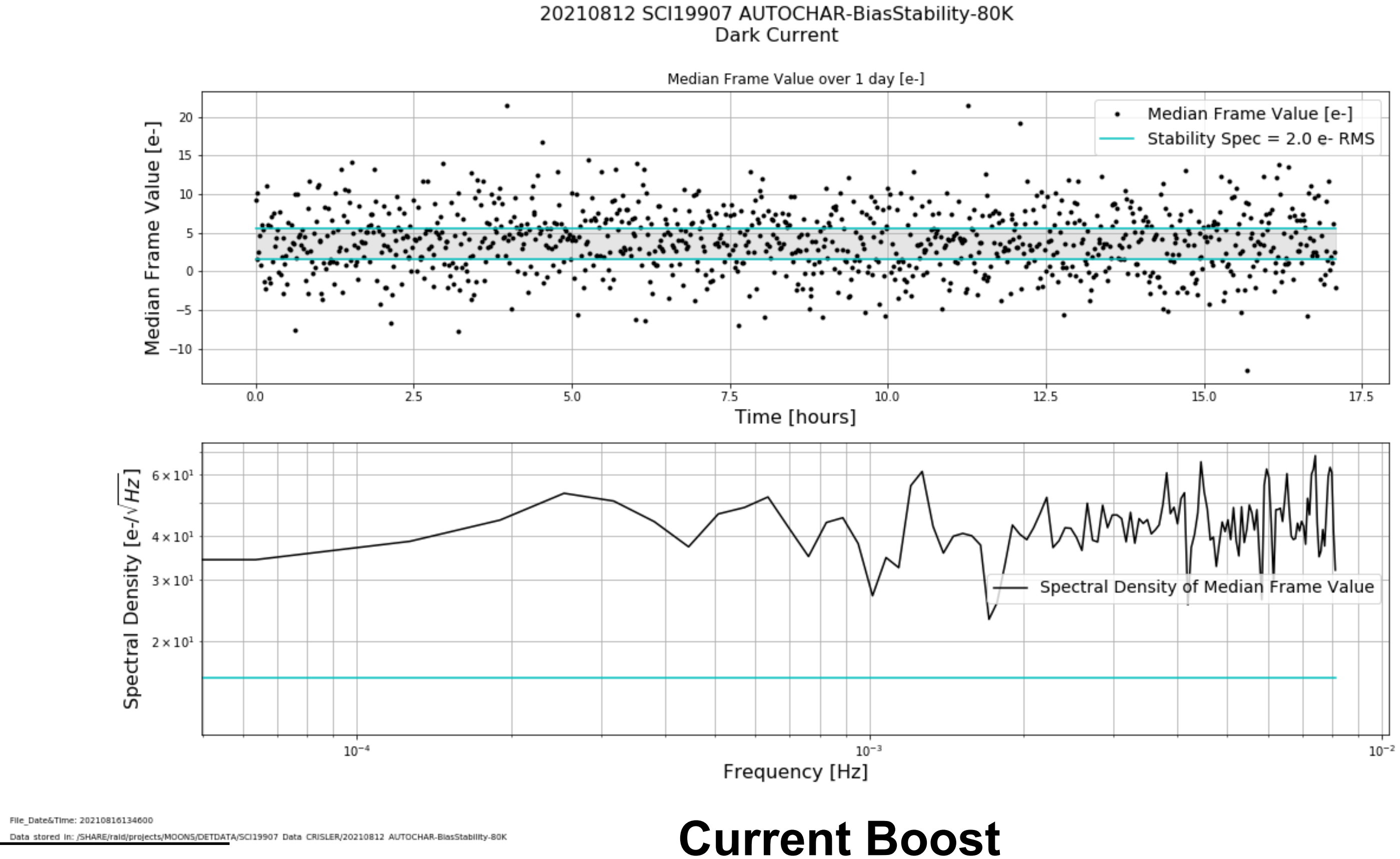




Bias Stability

- Take 1000x 60s darks and check the average frame value (UTR dark).
- Saw a 2.5x improvement in bias stability between using Current Boost Low Power and using Current Boost without low power mode. (Reg3 = 0x3190 vs 0x3090)





Current Boost

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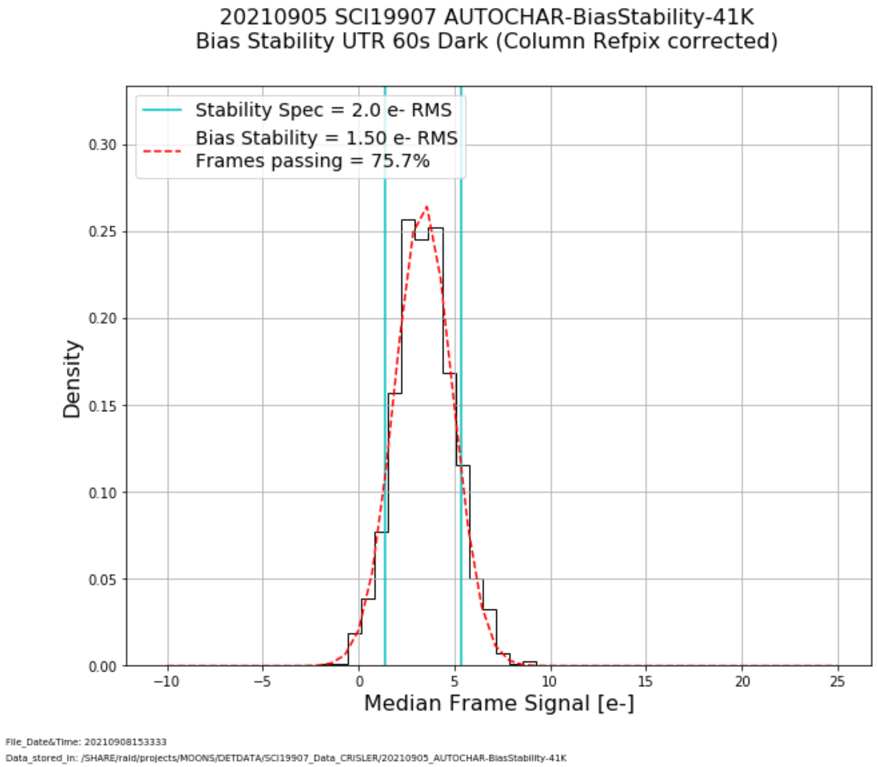
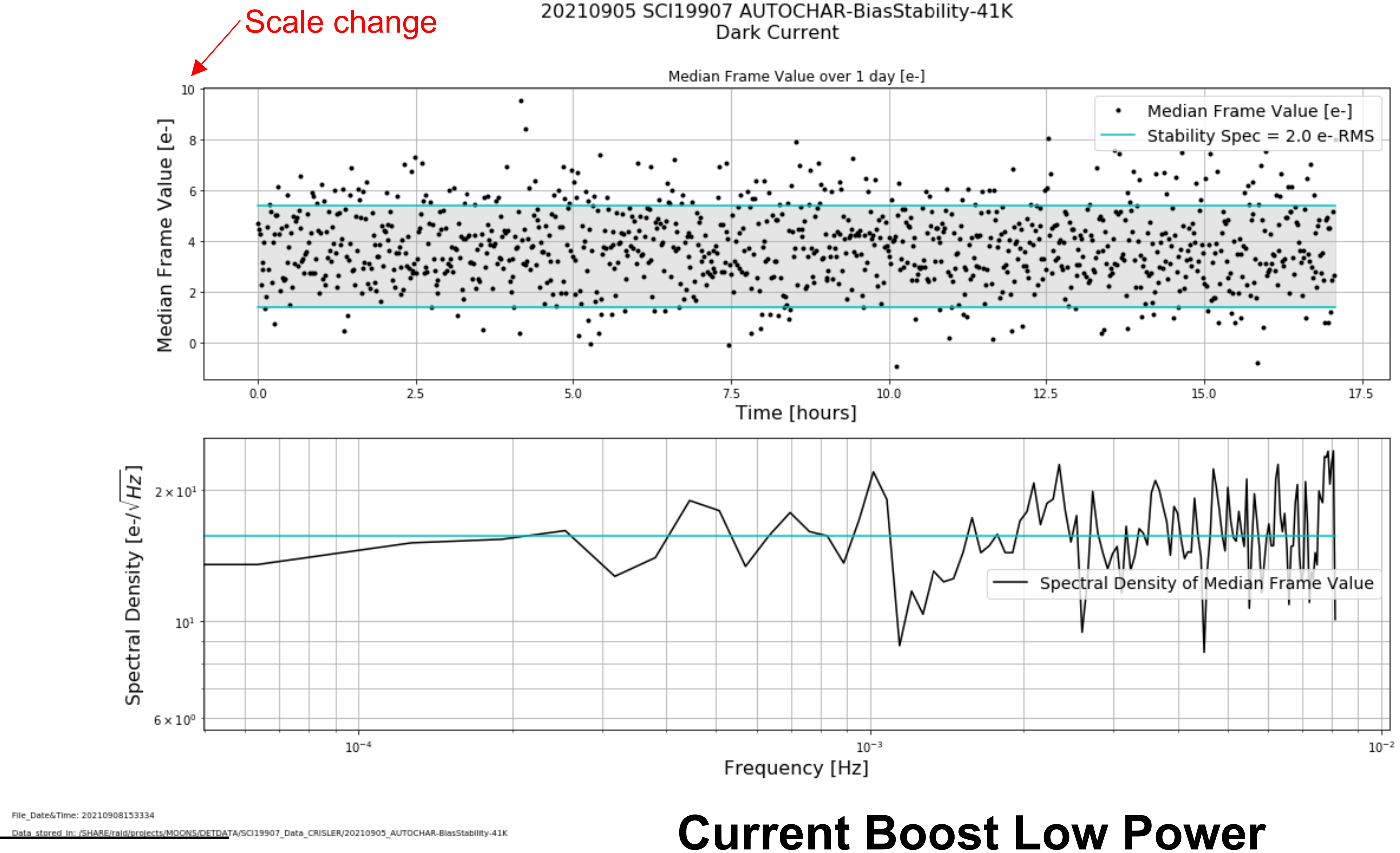




Current Boost Low Power

Data Classification: PUBLIC

Big performance table at 40K

	ENG-20370*	SCI-19907	SCI-19910	SCI-20372	SCI-20374
Dark Current (median)	0.0029 e-/px/s	0.0035 e-/px/s	0.008 e-/px/s	0.014 e-/px/s	0.008 e-/px/s
Glow per read (median)	0.051 e-/px/rd	0.037 e-/px/rd	0.053 e-/px/rd	0.043 e-/px/rd	0.014 e-/px/rd
Noise CDS, UTR 120s	10.0, 5.8 e- RMS	11.2, 4.6 e- RMS	11.7, 5.1 e- RMS	11.6, 5.6 e- RMS	9.9, 4.5 e- RMS
Persistence trap density	0.68%	0.20%	0.51%	2.52%	1.38%
QE @ 2 µm, (Teledyne, 77K)	96%	90%	97%	95%	89%
IPC (total)	2.75%	2.48%	2.99%	2.08%	1.98%
Gain	2.15 e-/ADU	2.01 e-/ADU	2.07 e-/ADU	2.29 e-/ADU	2.08 e-/ADU
Non-Linearity 5-50% FWC	1.19%	1.06%	1.29%	1.76%	1.23%
Full Well Capacity at 250mV bias	91 ke-	102 ke-	101 ke-	104 ke-	101 ke-
Operability (Teledyne definition)	93.62%	99.48%	99.39%	97.08%	98.26%
Amplifier Cross talk (median, max) 200 kpix/s	0.01%, 0.05%	0.01%, 0.19%	0.04%, X (affected by noise)	<0.01%, 0.05%	<0.01%, 0.04%
Bias Stability (e- RMS)	3.8* e- RMS	1.2 e- RMS	1.9 e- RMS	1.3 e- RMS	1.2 e- RMS
PEDs	1, (mostly) removed via RD	0	1	2, 1 removed via CD	0

*Operating using Current Boost without low power option

Data Classification: PUBLIC

Characterization Data Products

Data Classification: PUBLIC

Characterization data products

Maps (used for modelling)

- Persistence trap density
- Gain per pixel
- QE
- Dark current
- Glow per read
- Noise (CDS and UTR)
- Bad pixels
- Etc.

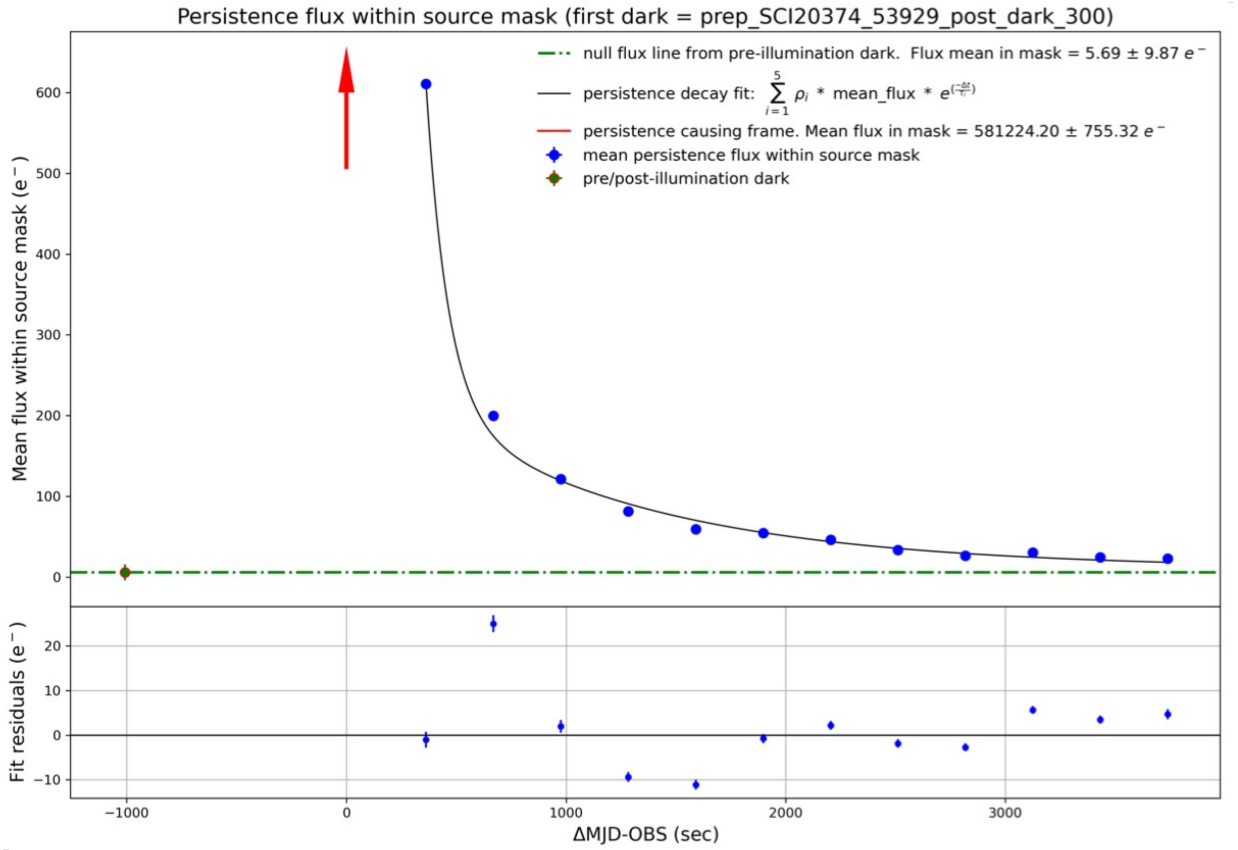
Values (used to verify requirements)

- Median persistence trap density
- Median Gain (low signal)
- Median QE
- Median dark current
- Median glow per read
- Median IPC
- Median Noise (CDS and UTR)
- Fraction Operable pixels
- Etc.

Example data product use: persistence correction

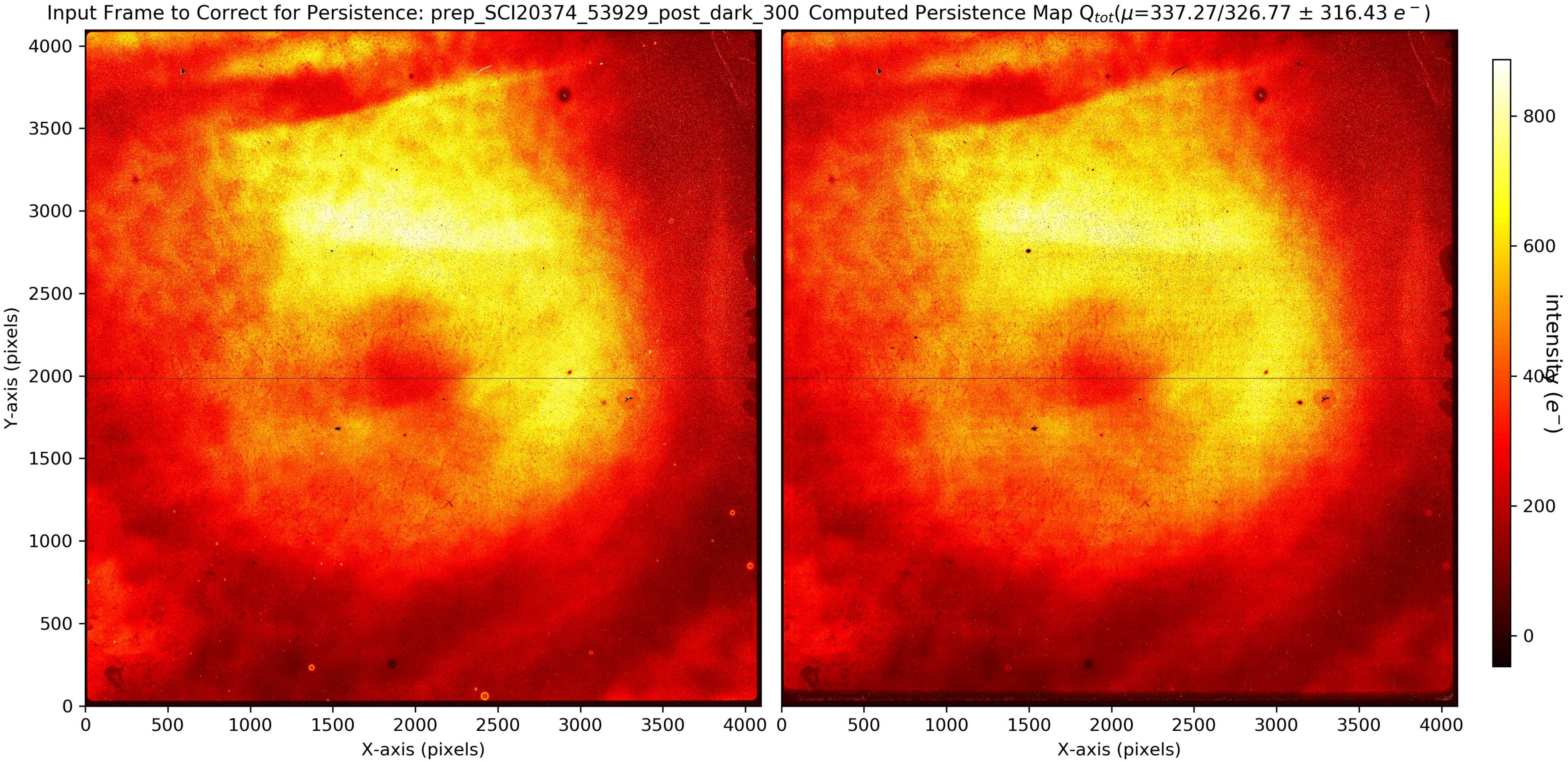
Workflow

- Persistence trap density map and time constant vector produced in characterization program.
- Pipeline team processes data products for each detector and integrates them into ESO Data Quality pipeline.
- DQ pipeline runs predictive persistence model on all exposures from previous few hours and calculates a predicted persistence map for each exposure.
- Scientists can use the predicted persistence map to correct their science exposures.



See: *Padovani et al. ESO Messenger Dec. 2022*
https://doi.eso.org/10.18727/0722-6691/5286
Check out Mark Neeser's presentation at SPIE 2024

Example data product use: persistence correction



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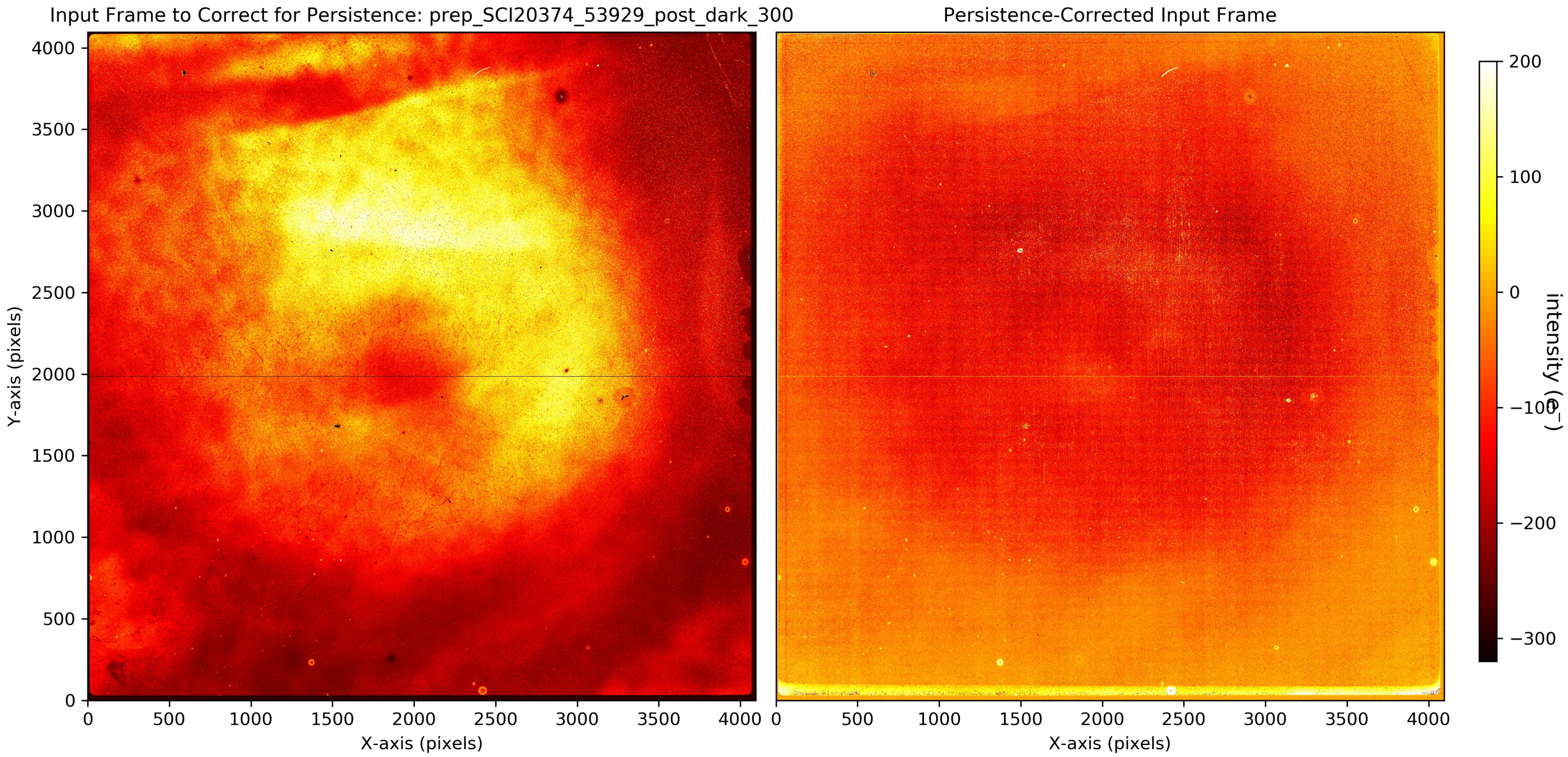
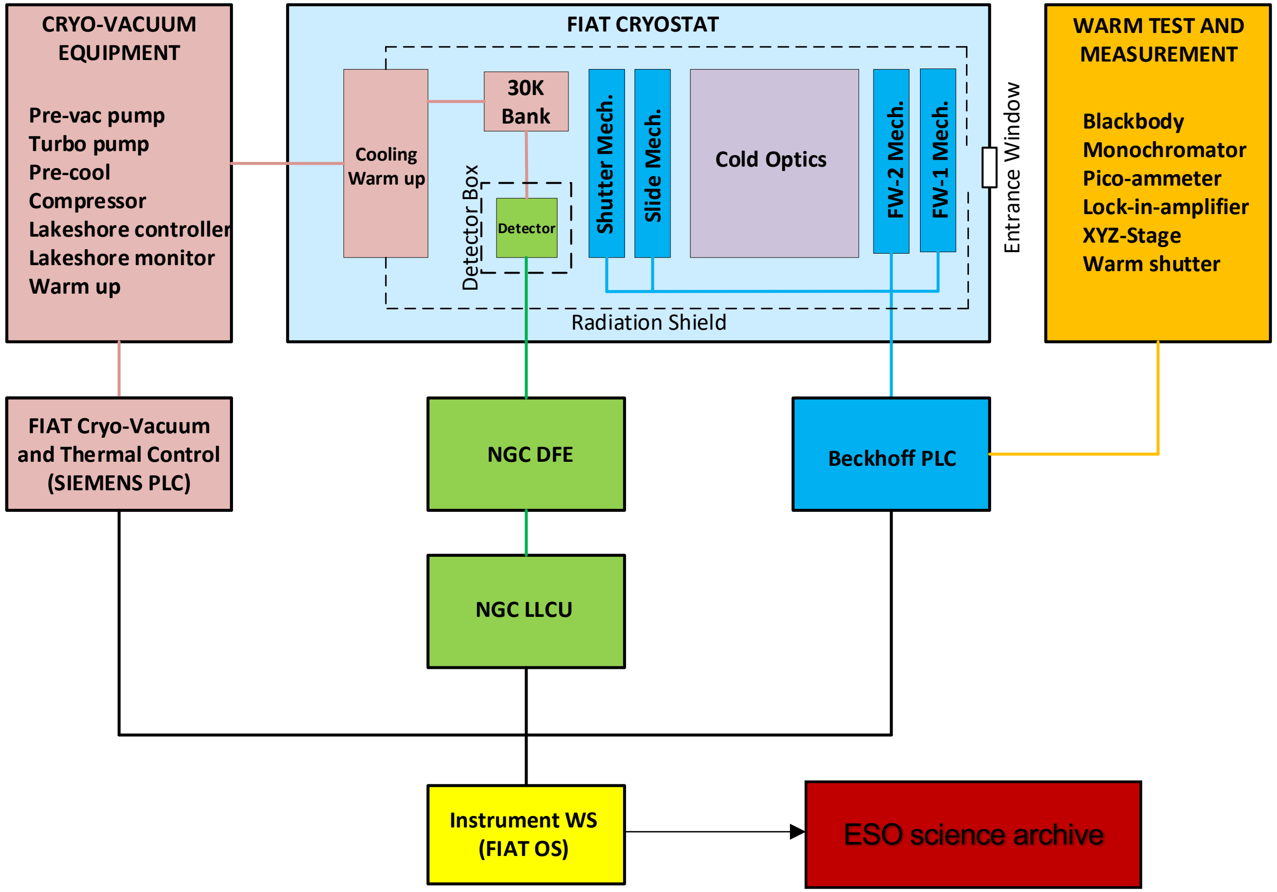


Data Classification: PUBLIC

For the ELT: characterization data to the archive

- ELT first generation instruments science detectors:
  - 17x H4RG-15 detectors
  - 5x H2RG
  - 1x GEOSNAP
  - 4x CCDs (TBC)
- All characterized in similar way as MOONS detectors.
- All data from characterization automatically uploaded to the ESO archive and available for instrument consortia to use for modelling and tracking detector performance over time.

Detector characterization facility block diagram



See: *Bezawada et al. AN Apr. 2023*
https://doi.org/10.1002/asna.20230061

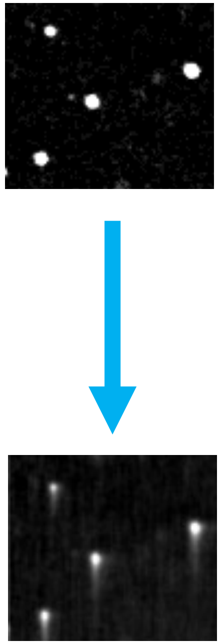
Modelling with Pyxel

Open Source Detector modelling framework

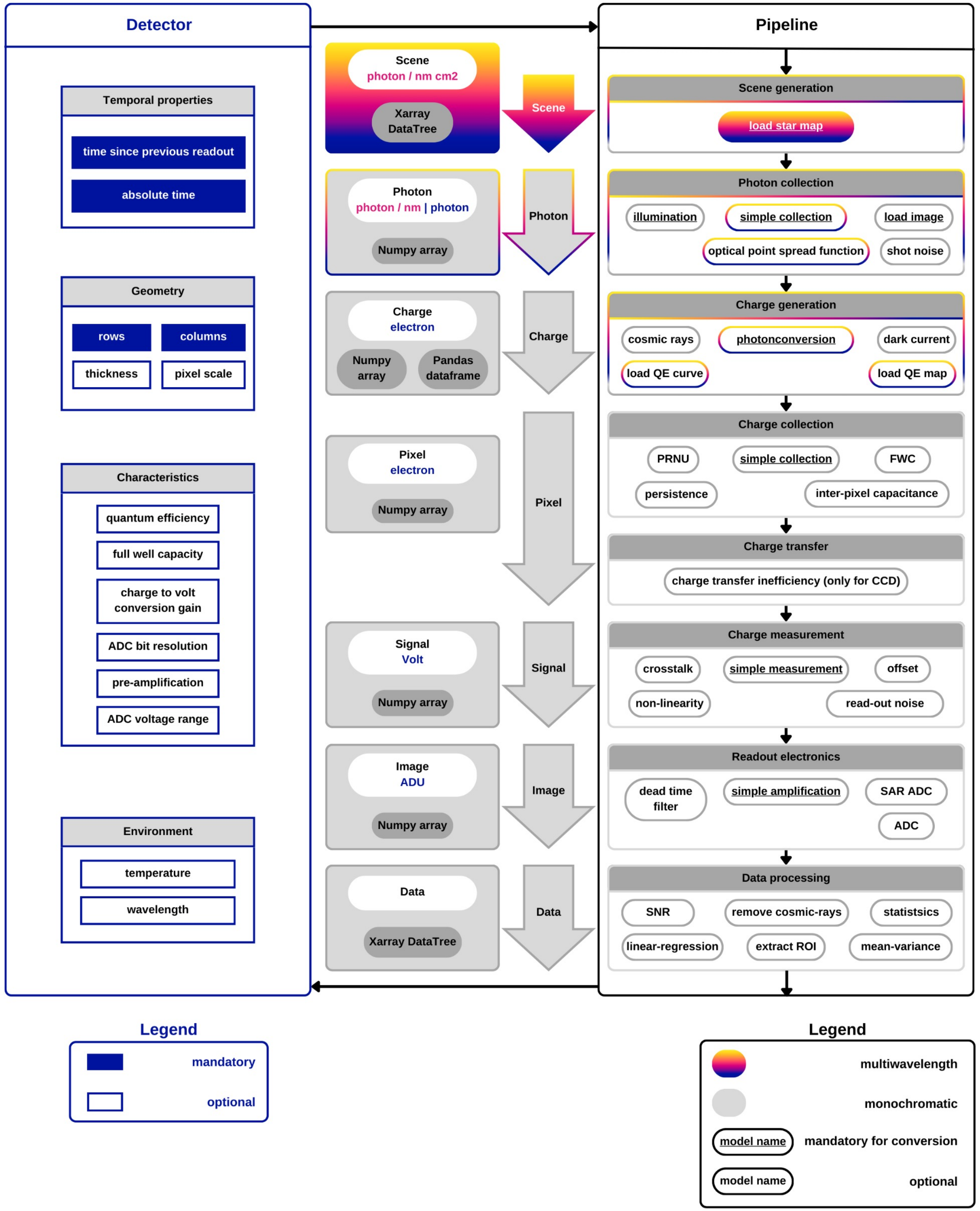
Pyxel architecture (v2.0)

- Pyxel is a novel, end-to-end detection chain simulation framework in Python.
- It hosts and combines existing and new models of detector effects.
- Open-source multi-purpose tool supporting instrument development during all phases.

Input photon distribution



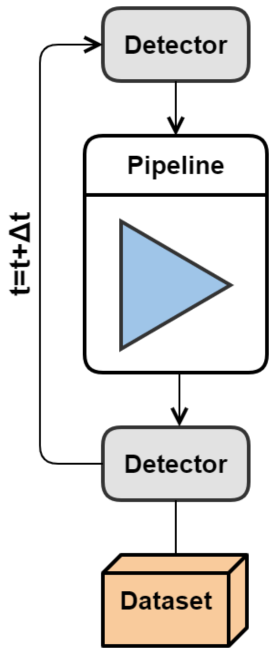
Output image



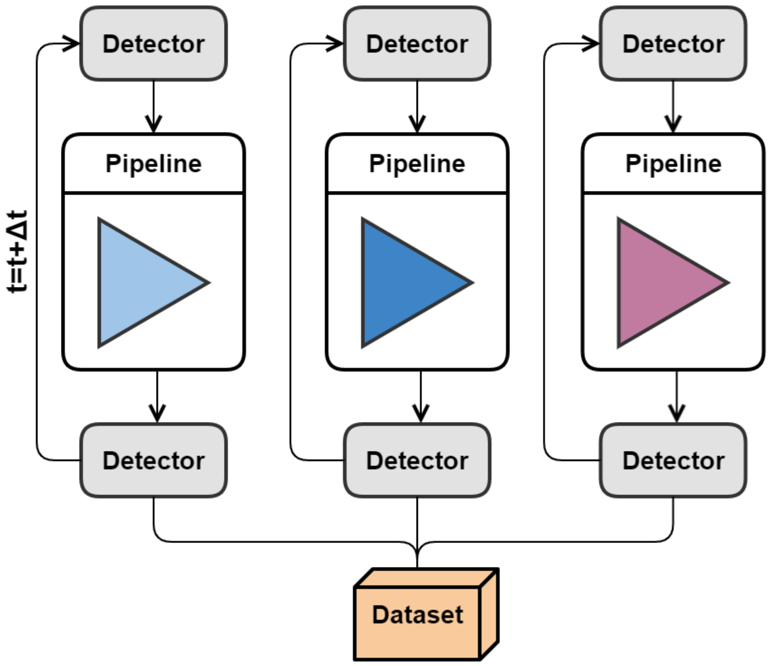
Data Classification: PUBLIC

Pyxel: Three running modes

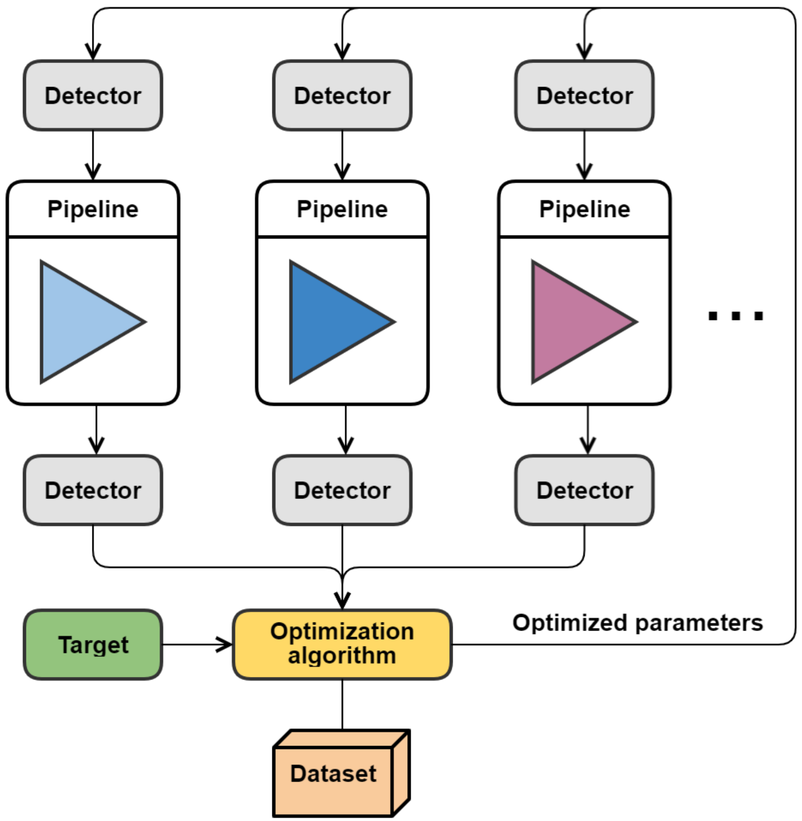
Exposure mode
the simple mode for health check or simulation of non-destructive readout



Observation mode
multiple pipelines with a range of model or detector parameters (parallelization possible)

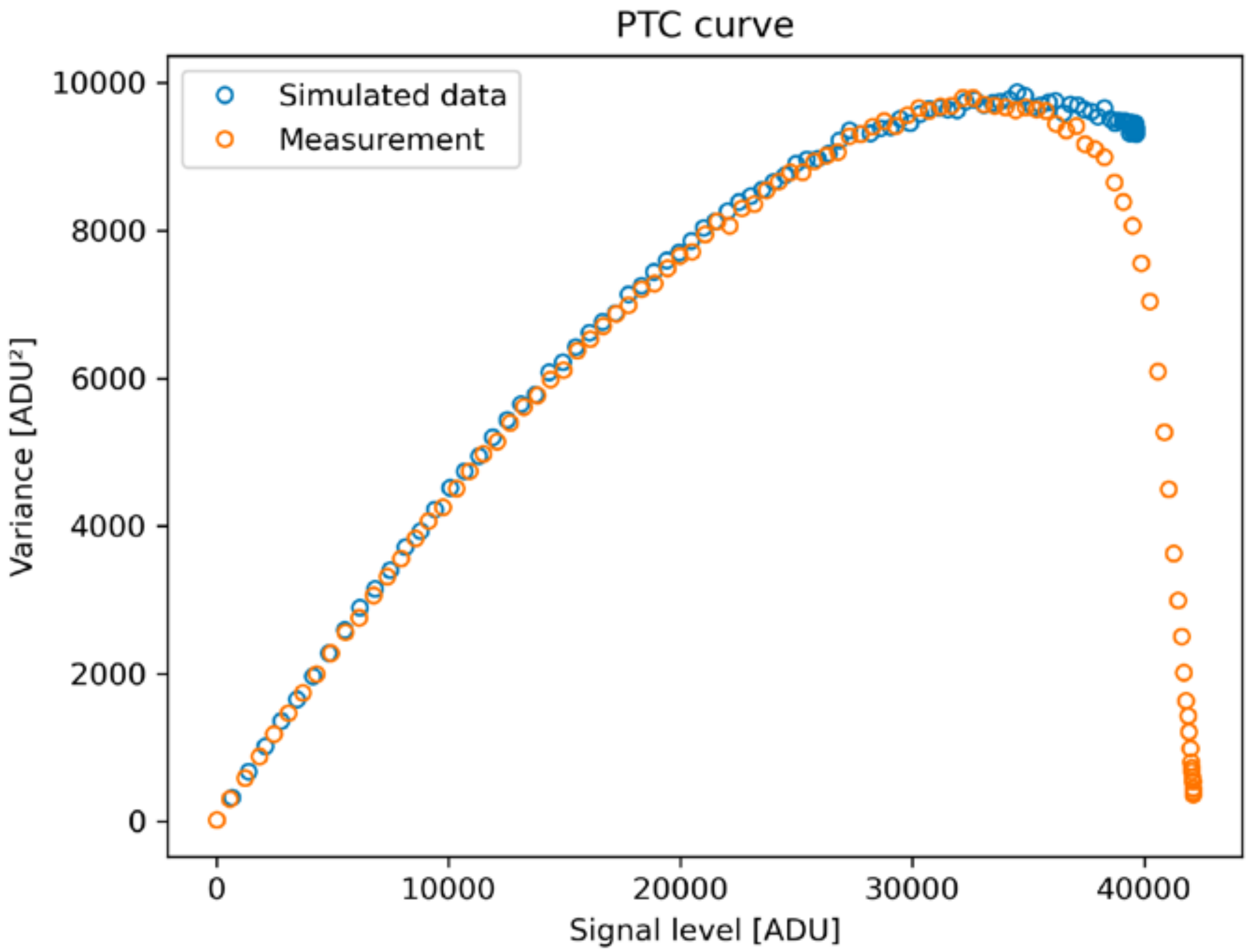


Calibration mode
optimize model or detector parameters to fit target data sets (model fitting, instrument optimization). Can run on a grid of computers or a computer cluster.



Output example: calibration mode

- The pyxel H4RG generic pipeline is calibrated against some MOONS lab data (PTC).
- Comparison between measured photon transfer curve and simulated one (for best fitting params)
- Output is a calibrated model: a physical model for non-linearity in SFD type pixel. The free params are: donor density, diode diameter, and fixed capacitance C_f.
- Good match until saturation is reached (this model does not quite reach saturation).



See: Arko et al. JATIS Dec. 2022
https://doi.org/10.1117/1.JATIS.8.4.048002

Data Classification: PUBLIC

Pyxel: try it yourself

- **Pyxel** - the collaborative detection simulation framework - **version 2.0 is out!**
- Easier than ever to install: one-liner installation
- Easier than ever to try: Running on binder, runs remotely on browser, no install
- Easier than ever to learn:
    - Tutorials and examples available
    - Detailed documentation
- Very flexible framework: please abuse it and surprise us!
- Can be embedded in your existing simulator and vice versa
- **Join the community and make Pyxel the engine behind your simulator!**

https://esa.gitlab.io/pyxel/

Check out the Pyxel Demo at SPIE 2024!

Conclusions

H4RG-15 detectors for MOONS fully characterized and standardized data products available.

Good performance over the 5 devices, with some variability (especially in persistence). Program spurred development of Rev2 ROIC for H4RG-15 to reduce glow.

MOONS Characterization Data products are in use for pipeline science data correction as well as for detector modelling. (Future: ELT projects)

Let's discuss at coffee break:

What uses do detector characterization data products from the lab have? How well do these detector properties have to be characterized for each use?

Share examples from your own projects.

Thank you!

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