First Thoughts
H4RG-17940 sample data

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for the WFIRST Project Team

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Context

- At the last Princeton Meeting, the DCL provided sample data for WFIRST SCA H4RG-17940
- These charts are based on a first “quick look” at these data. All conclusions are preliminary
  - Time only to focus on dark performance so far
  - Will turn to illuminated performance soon
- Independent confirmation by FSWG members would be good! We have the data on a disk here for those who want them
- These charts provide an idea of the kinds of things that can be done with the sample data

Scan for these charts

Executive Summary

- **From the parameters that I looked at, H4RG-17940 is a really nice detector! The data provided by the Goddard Detector Characterization Laboratory (DCL) are very high quality. They provide excellent insight into what this sensor chip assembly (SCA) is capable of**
- The readout integrated circuit (ROIC) seems to have good performance
  - Nothing atypical noted
- The HgCdTe seems to have good dark performance
  - Nothing atypical noted
- Total noise is a little high, but can probably be made better
  - Conversion gain at low signal may improve with lower flux illumination. Would be nice to get some lower flux data. Should help noise
  - Clear correlated noise imprints suggestive of thermal disturbance and/or bias instabilities are seen (based on H2RG & other HgCdTe experience). These operating environment effects should not be attributed to the H4RG-10. We should aim to minimize these with good system engineering
  - As the DCL has already shown, higher speed clocking may help, but would affect power dissipation and onboard data rates
  - Alternatively, tuning the measurement bandwidth to the WFI's PSF (optics + IPC + anything else…) may reduce noise at the current clocking speed

Basic performance parameters

Types of Data

- These data are currently available with more to come

AAA_README.docx
AAA_README.pdf
AAB_CONTENTS.txt
jl15_100k_0p8m0p3_dk2h_05.ff.fits
jl15_100k_0p8m0p3_dk2h_06.ff.fits
jl15_100k_0p8m0p3_dk2h_07.ff.fits
jl16_100k_0p8m0p3_gain20k_1400nm_06.ff.fits
jl16_100k_0p8m0p3_gain20k_1400nm_07.ff.fits
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AAA_README.txt
jl16_100k_0p8m0p3_gain4k_1400nm_07.ff.fits
jl16_100k_0p8m0p3_gain4k_1400nm_08.ff.fits
jl16_100k_0p8m0p3_gain4k_1400nm_09.ff.fits

2 hour, sparsely sampled darks

1.4 μm illumination to 20×10^3 e^-

100 frame SUTR darks for measuring total noise

“Flats” at 2 colors

Data for measuring persistence

1.4 μm illumination to 4×10^3 K e^-. Useful for measuring conversion gain, e^-/DN

Performance results summary

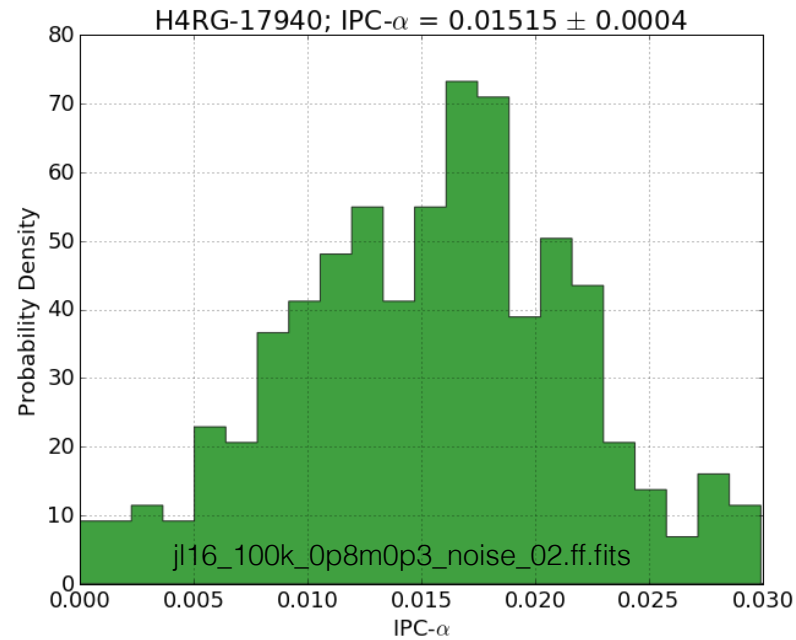
H4RG-17940 Analysis Summary

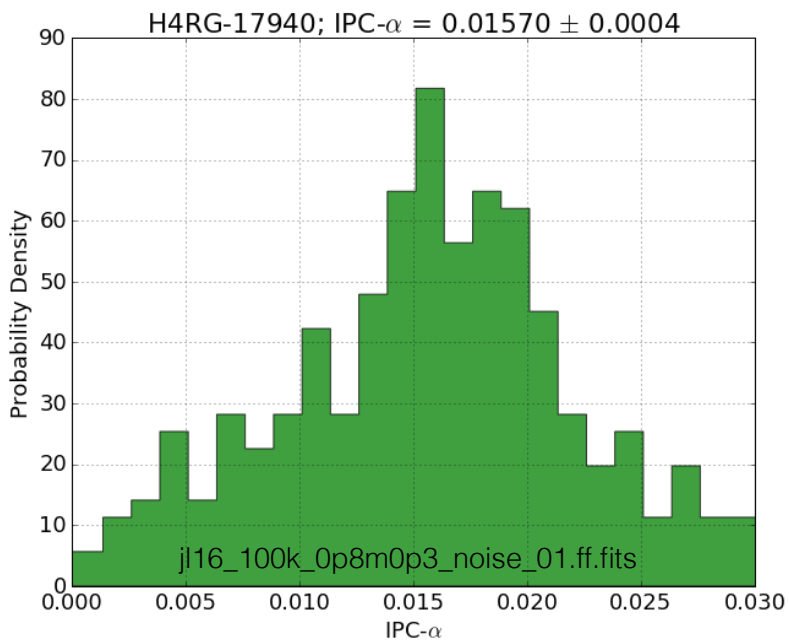
Test	DCL	Me	Comment
IPC-*α*	0.0182	0.01551 ± .0004	Discuss with DCL. Potential explanation is charge diffusion. DCL measurement used ^{55}Fe x-rays which will include some charge diffusion. The measurement reported here should be free from charge diffusion
g_c	0.445 e^-/DN	0.412 ± .04 e^-/DN	Concur
Mean dark current	0.001 e^-/s	Unmeasurable	Concur. Unmeasurably small with the sample data
Total noise	4.8 e^-	5.6 e^-	Discuss

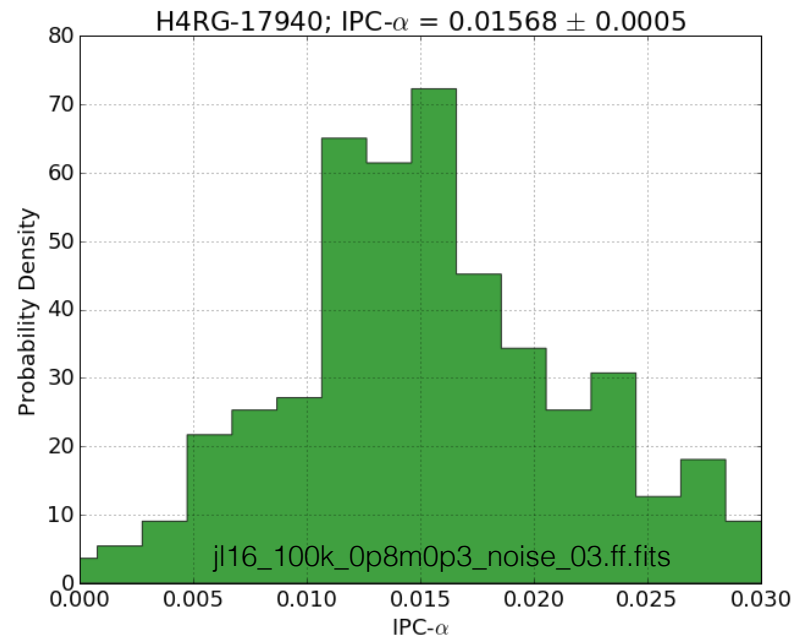
- Total noise is very sensitive to how the measurement is made and how the data are calibrated
- There are many potential explanations for the difference between the DCL's result and mine
- It would be helpful if others were to look at the data

IPC-α = 0.01551 ± .0004

- IPC-α estimated by looking for isolated "warm pixels"
  - 1000 DN < Signal < Full well
  - Left & right neighbors same to within read noise
  - Up & down neighbors same to within read noise
  - Mean of 4 corners zero to within read noise
  - Well modeled by a 2-parameter least squares fit

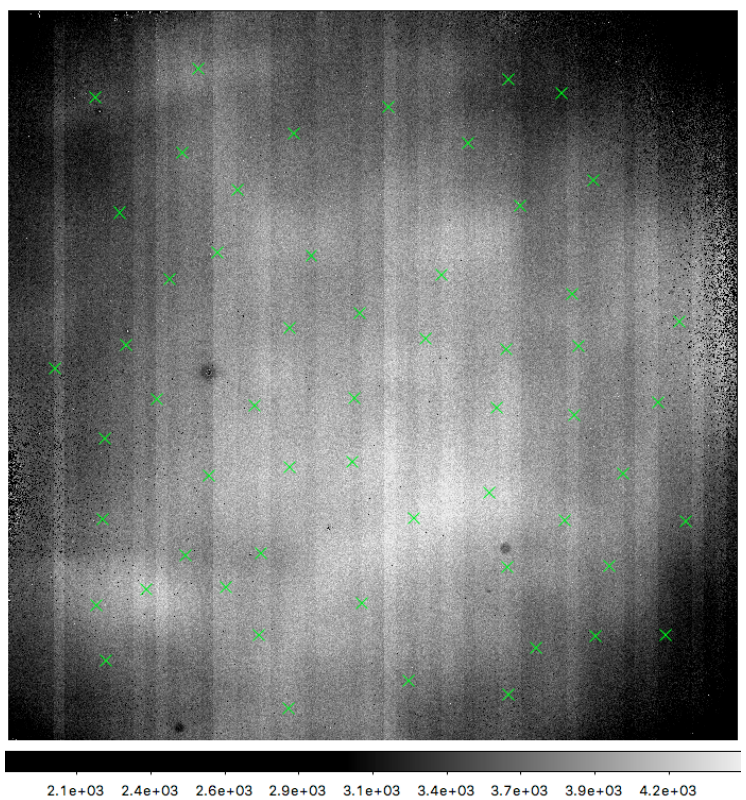


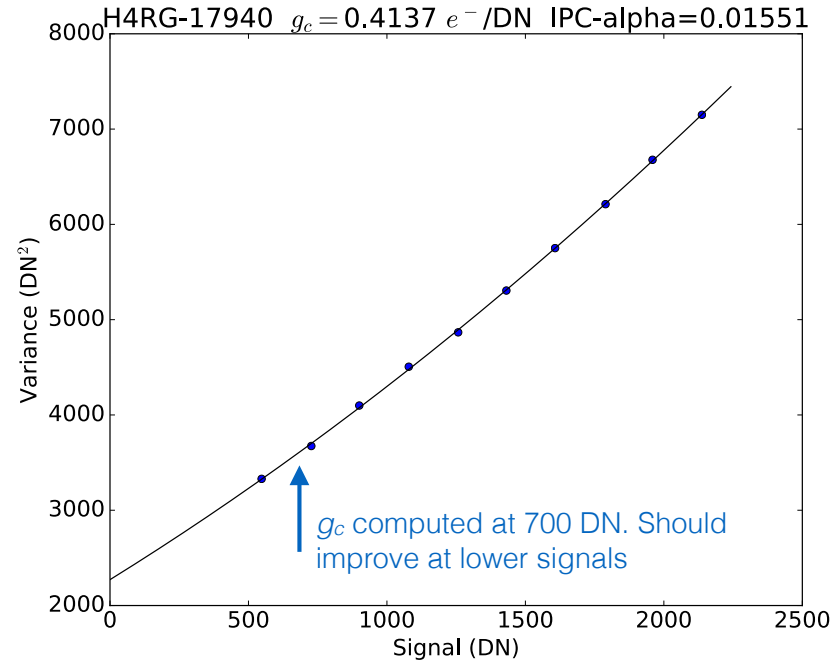


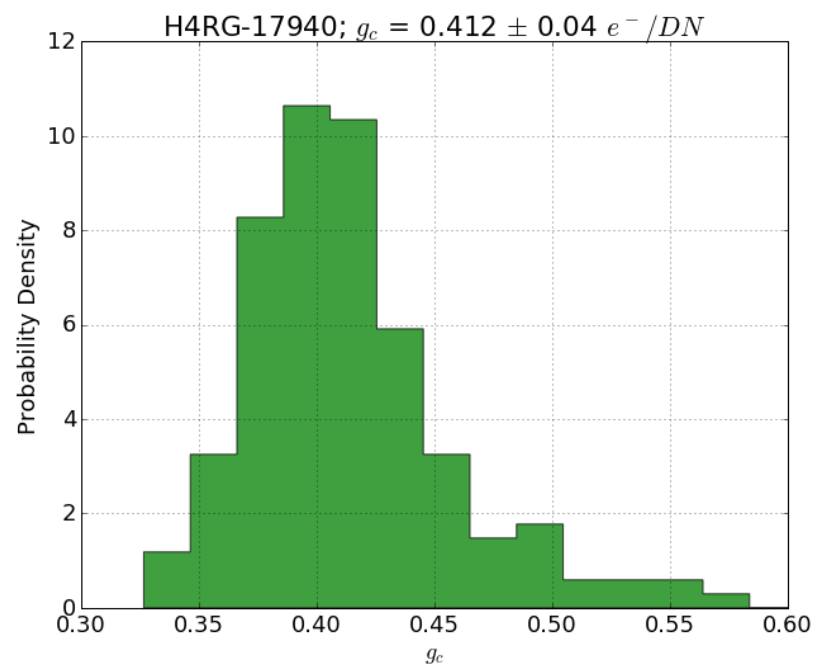


IPC corrected
low signal conversion gain = 0.412 ± .04 *e*-/DN

- Measured using plots of variance vs signal in differences
  - Data fitted to quadratic
  - g_c is 1/slope at 700 DN
- Computed using differences of 128x128 pixel regions of interest (ROI) centered on the green "x" marks below (2 exposures needed per green x)
- Plot at right is an example (many more like it)

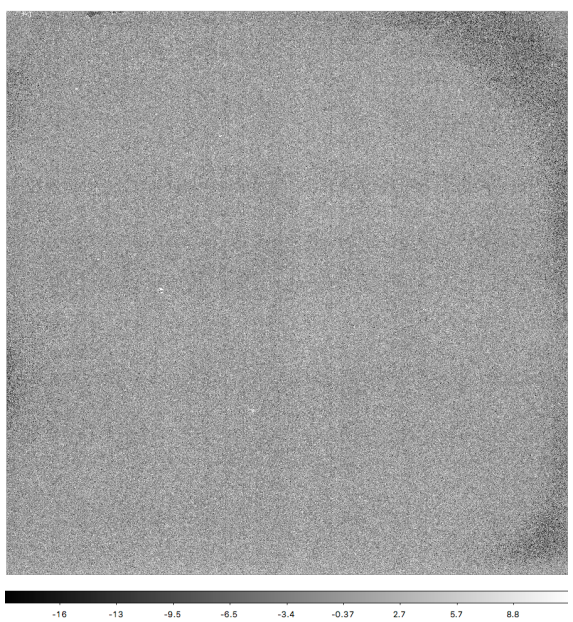




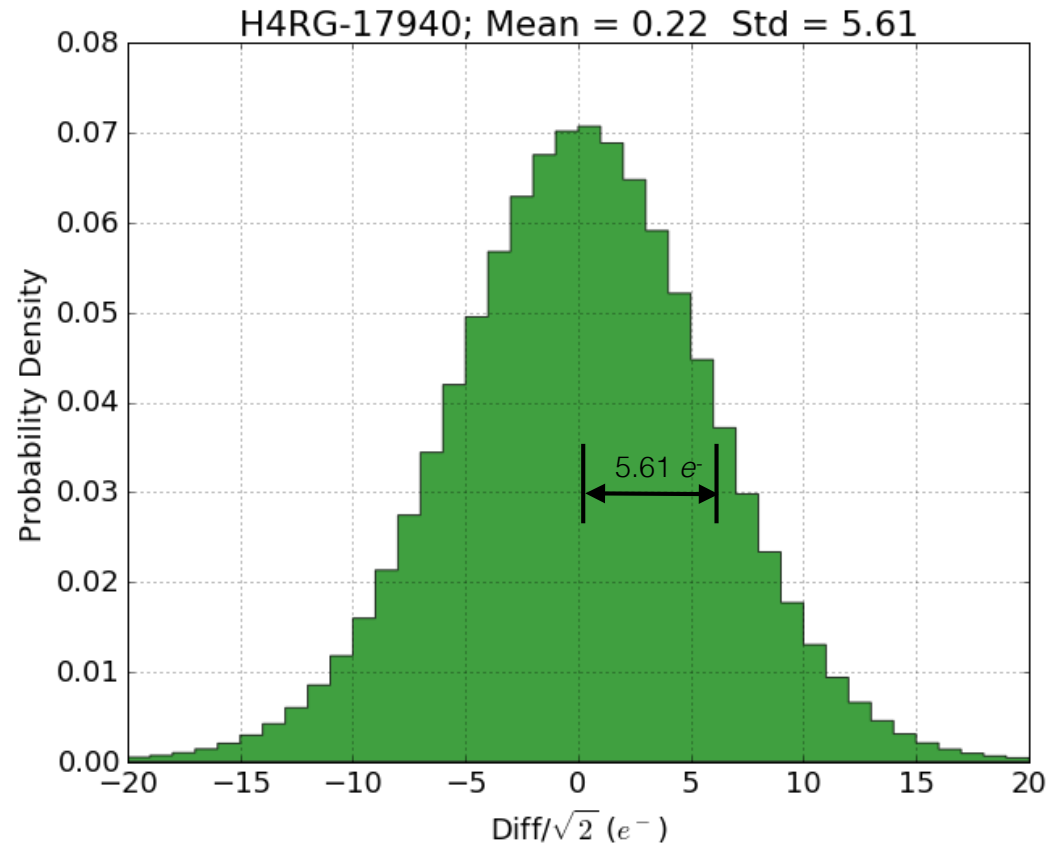


Total noise

- Median of 3 100 frame SUTR integrations
- Median dark current in regular pixels:
  - Undetectable with data provided
  - More data needed
- No glow noted
- Difference of two darks gives mean total noise ~ 5.6 *e*- rms



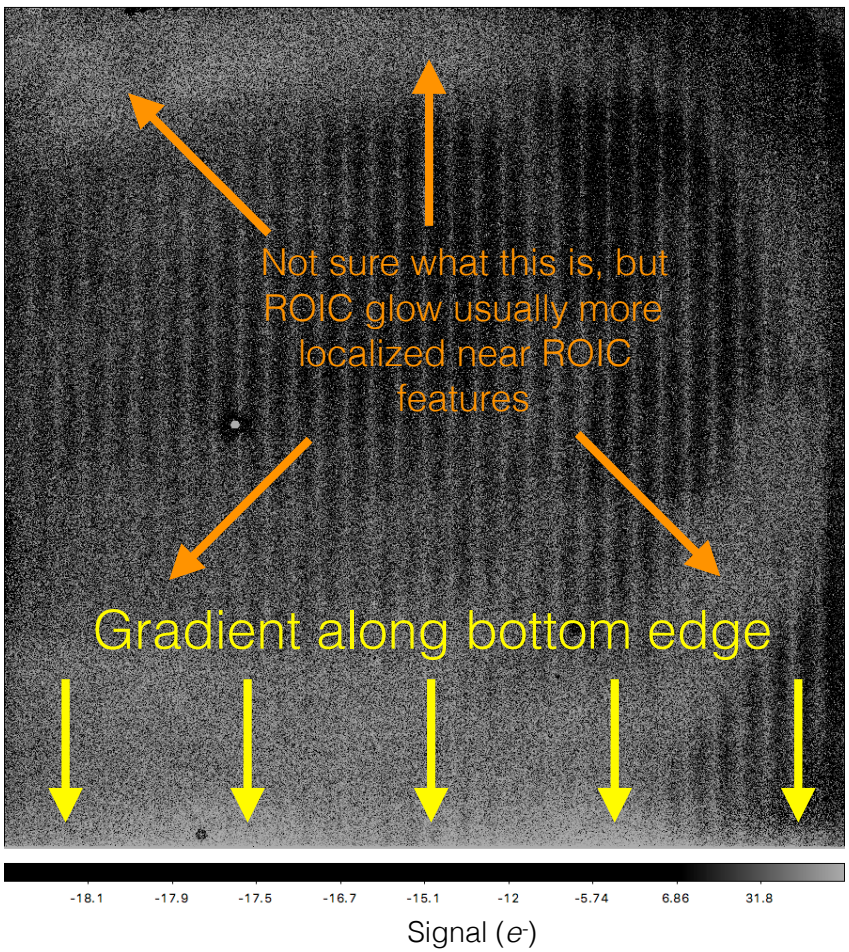
Integrated Charge (e^-)

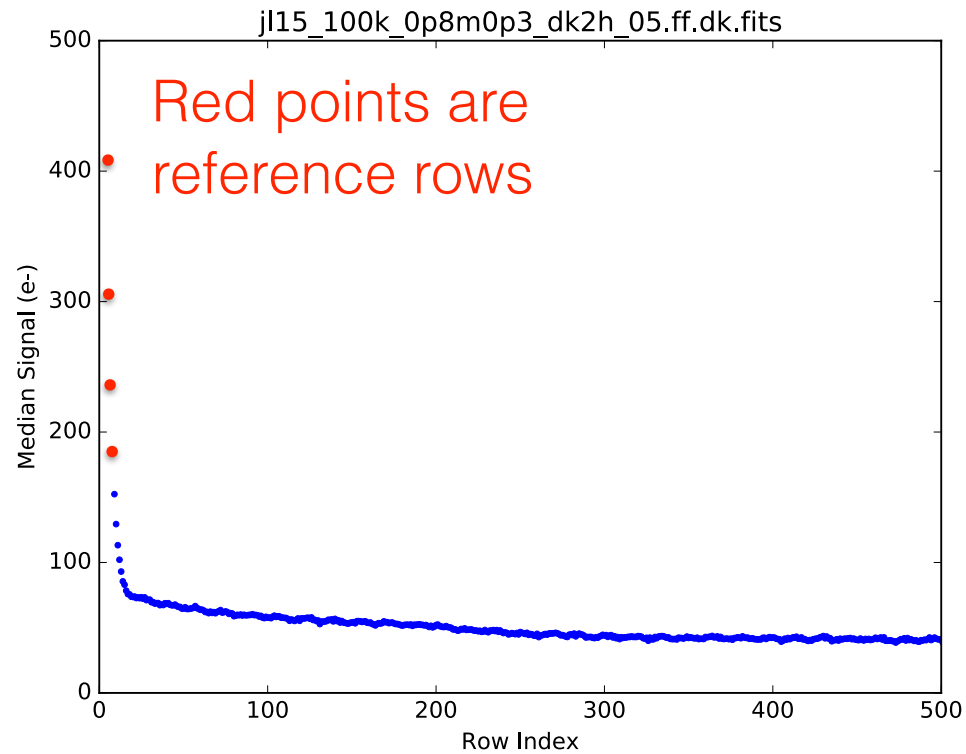


Other things noted…

Edge gradient in long darks is not glow

- Long darks have a gradient decreasing from a high value along the bottom edge
- Visible after: (1) fitting slopes and (2) reference correction using only pixels in area [-4:,:] (python notation) or [*,4092:4095] (IDL notation)
  - Noticed because standard reference correction schemes were failing
  - Extends into reference rows and likely thermal and/or electronic in origin. Potentially fixable by tuning the timing
  - Note also the bright vertical bars…
- Gradient is not ROIC glow. It extends into the reference pixels (see plot at lower right). More likely thermal and/or electrical settling
- Chaz Shapiro reports that it, "goes away", if one discards the first frame of the ramp before fitting (also consistent with thermal and/or electrical settling)



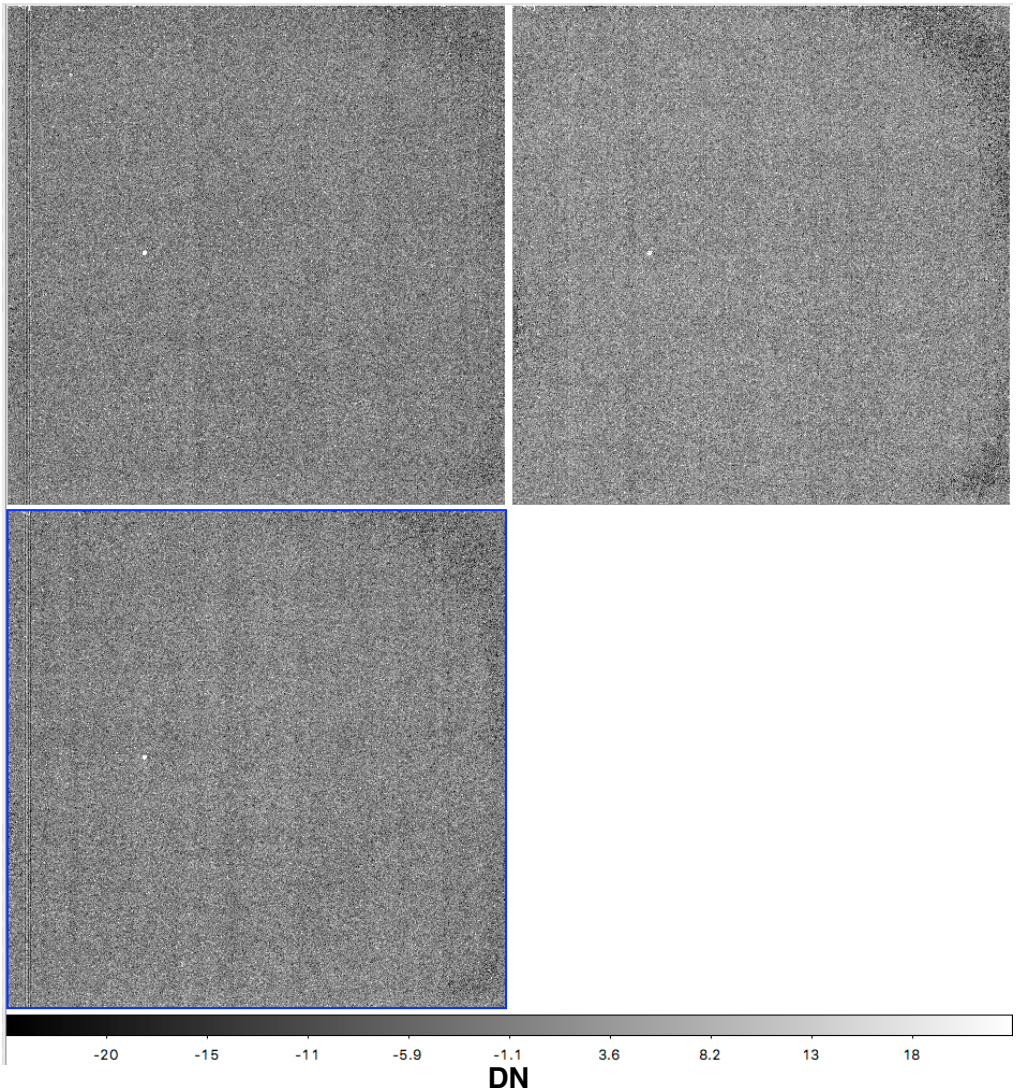


Median value of each row plotted against row index. The gradient extends into the 4 reference rows along the bottom (red points). The other two examples show the same behavior. Suggests that more settling time may be needed after NEWFRAME but before sampling pixels in this exposure mode.

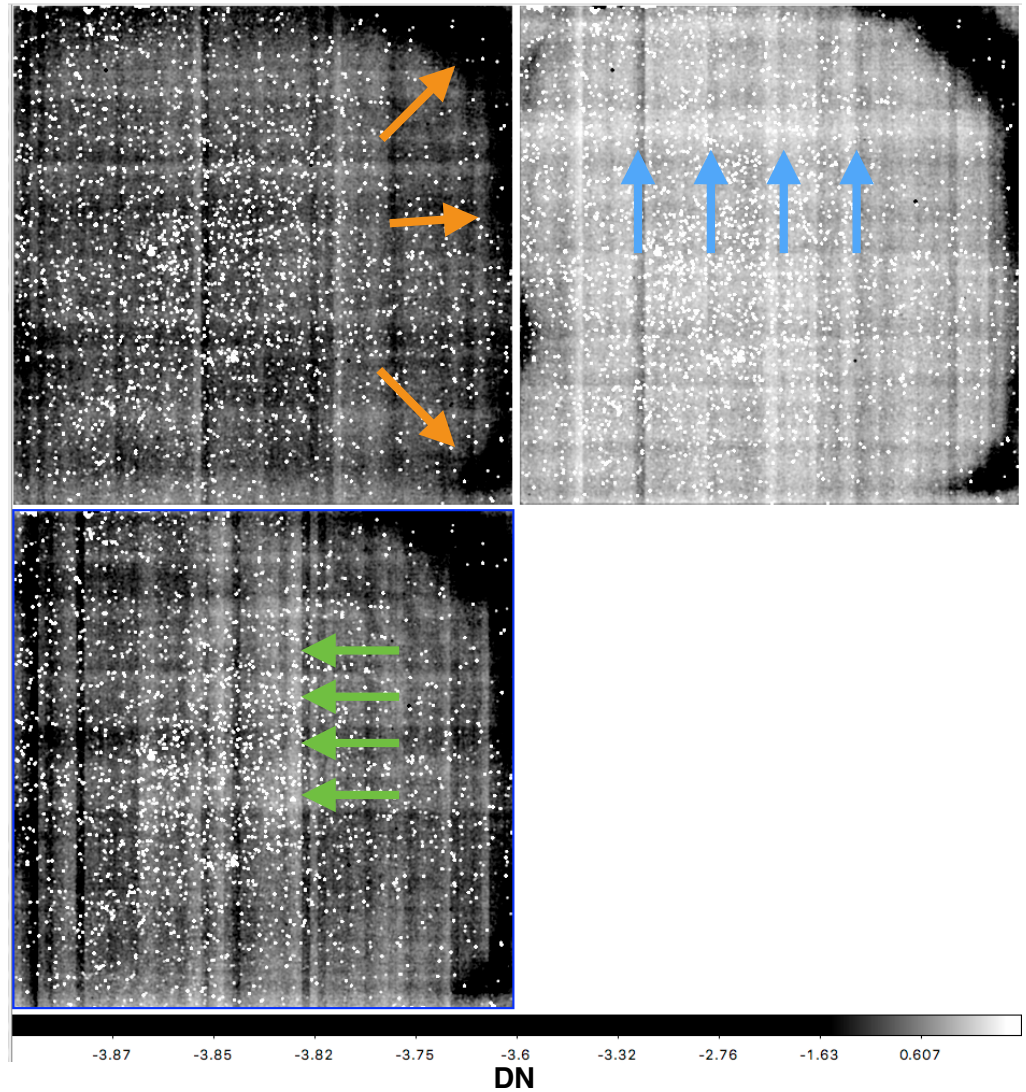
Small but detectable imprint from test system

(most of this stuff is probably not intrinsic to the H4RG-10)

Full resolution



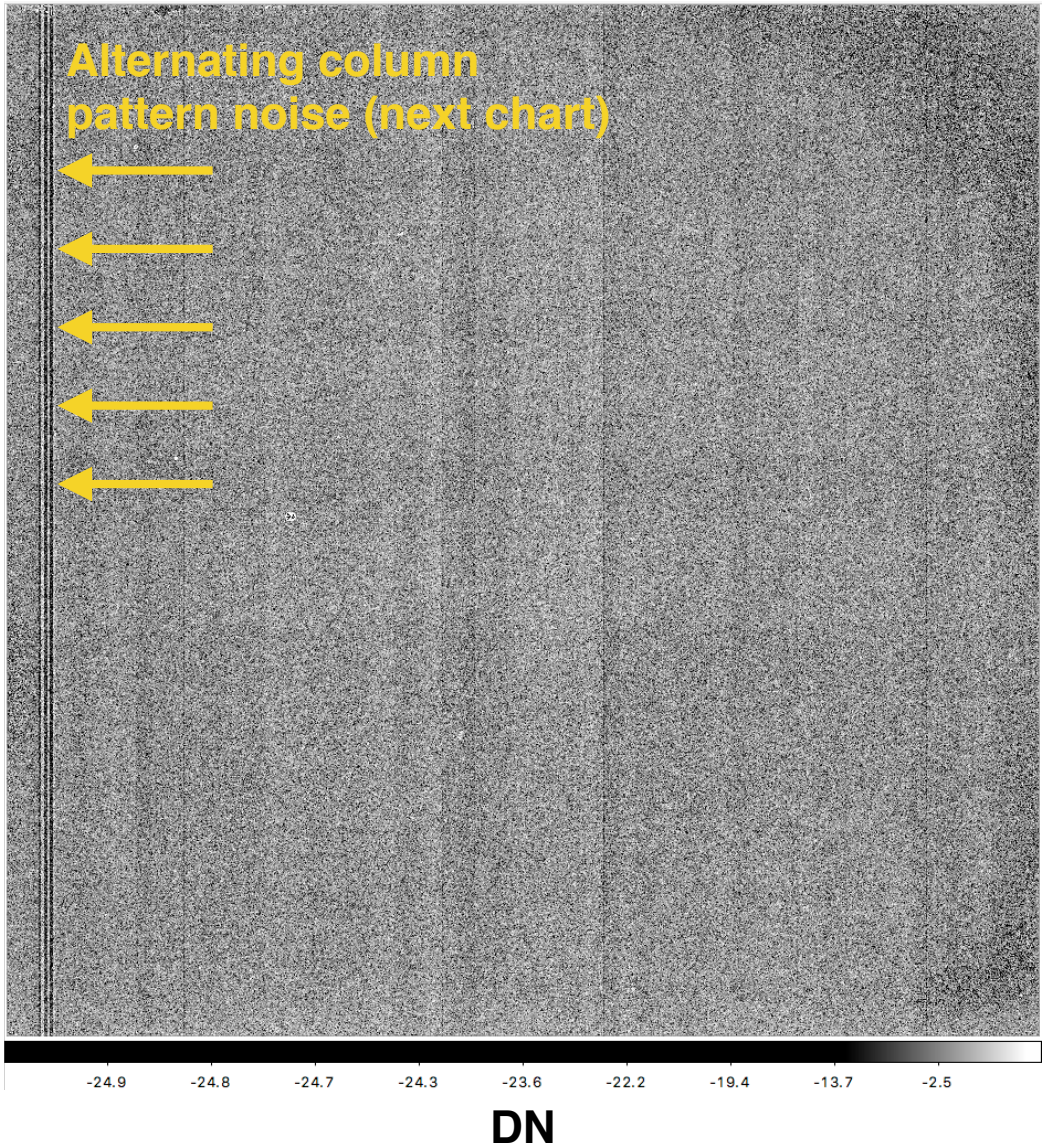
Gauss smoothed 16x16



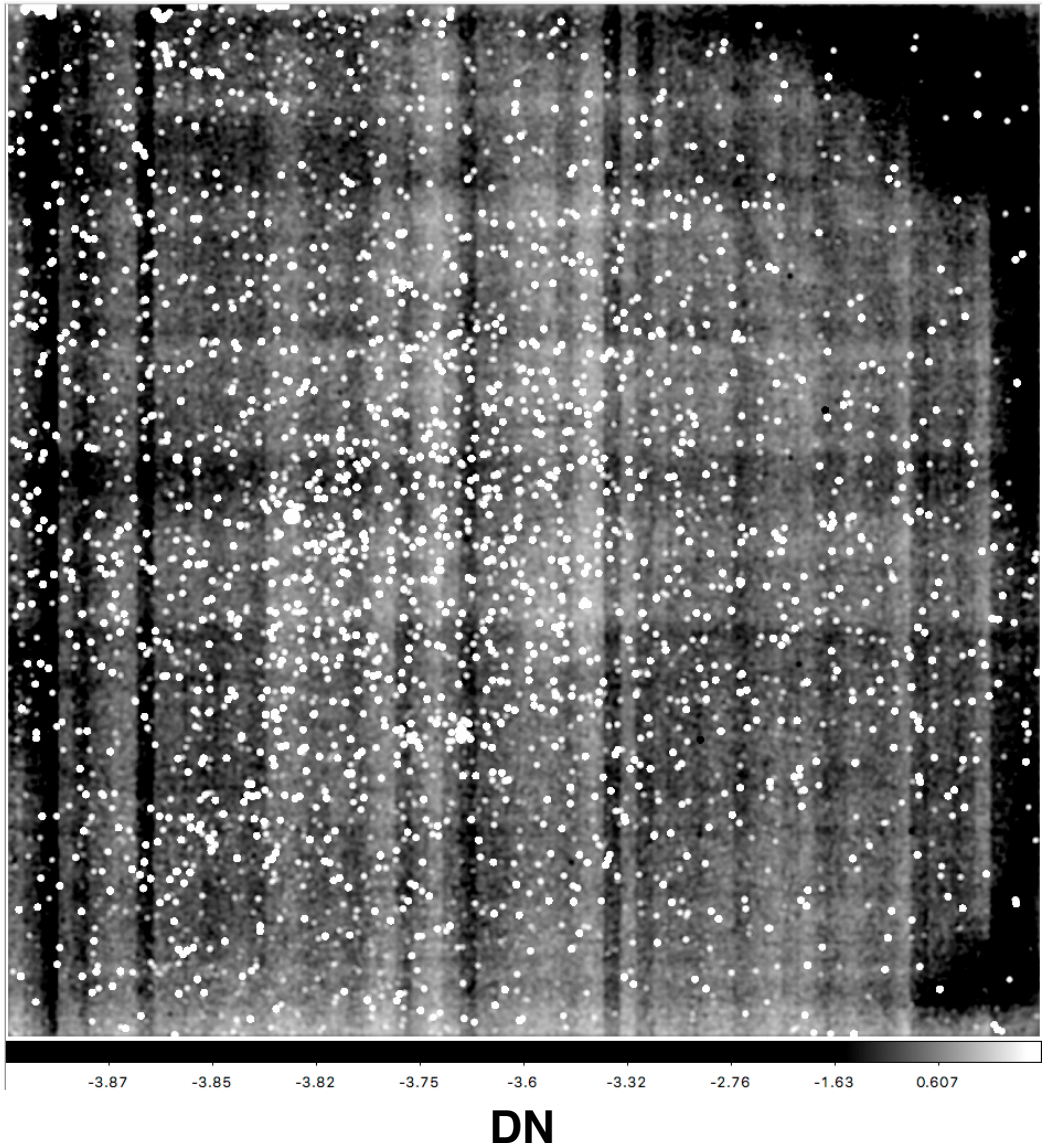
- [orange arrows] Not sure what darkening along right edge is (maybe just “picture frame” noise)…
- Small pedestal drifts noted, probably environmental in origin (thermal/electric disturbance)
- [blue arrows] Horizontal bars and bands correlate across outputs, probably environmental (readout electronics) in origin
- [green arrows] Vertical striping is reference correction residuals. I used only pixels [-4:,:], which tend to be most stable in prototype systems
- Alternating column pattern noise noticed in one output (following charts)

Zooming in on one…

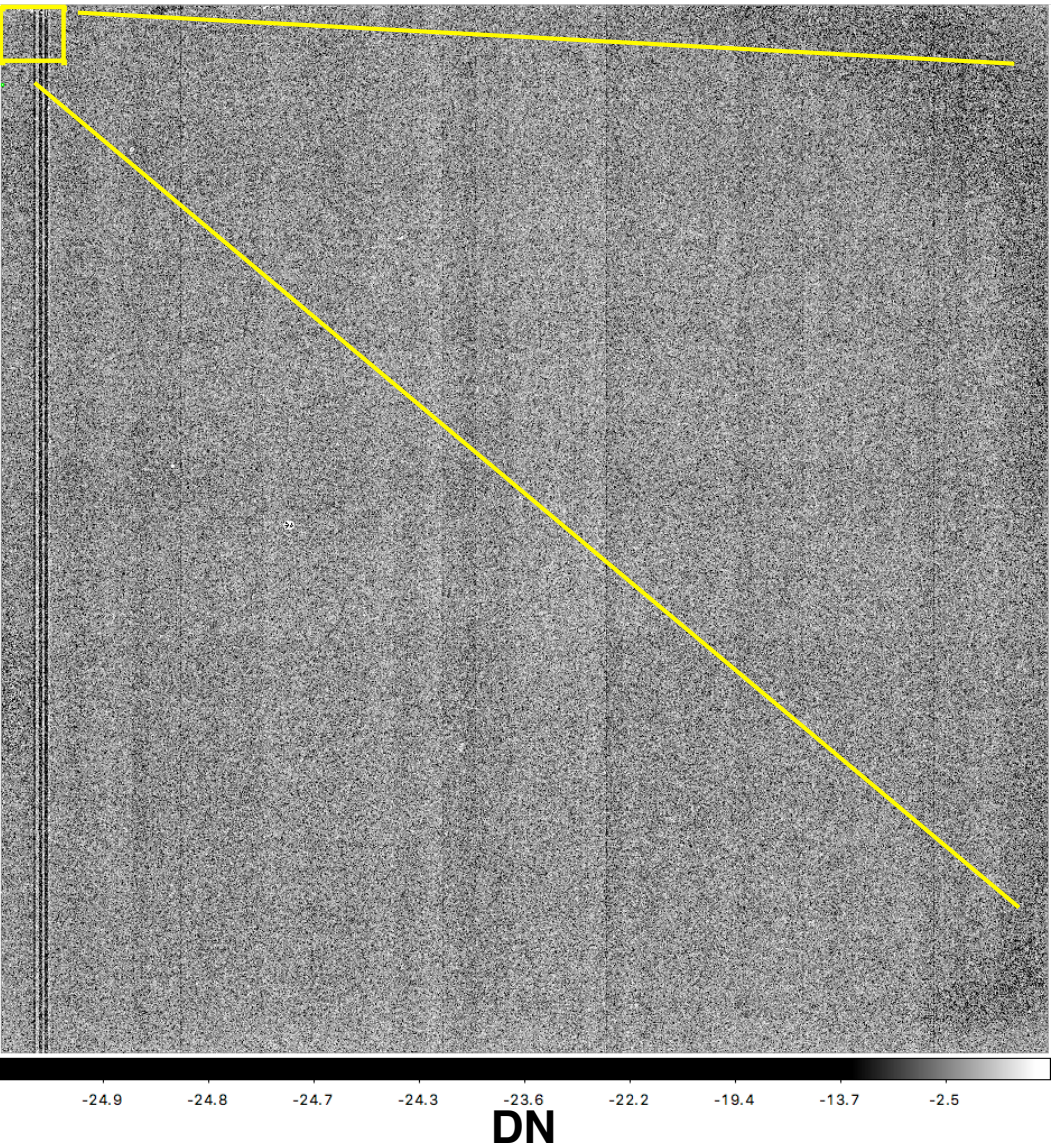
Full resolution

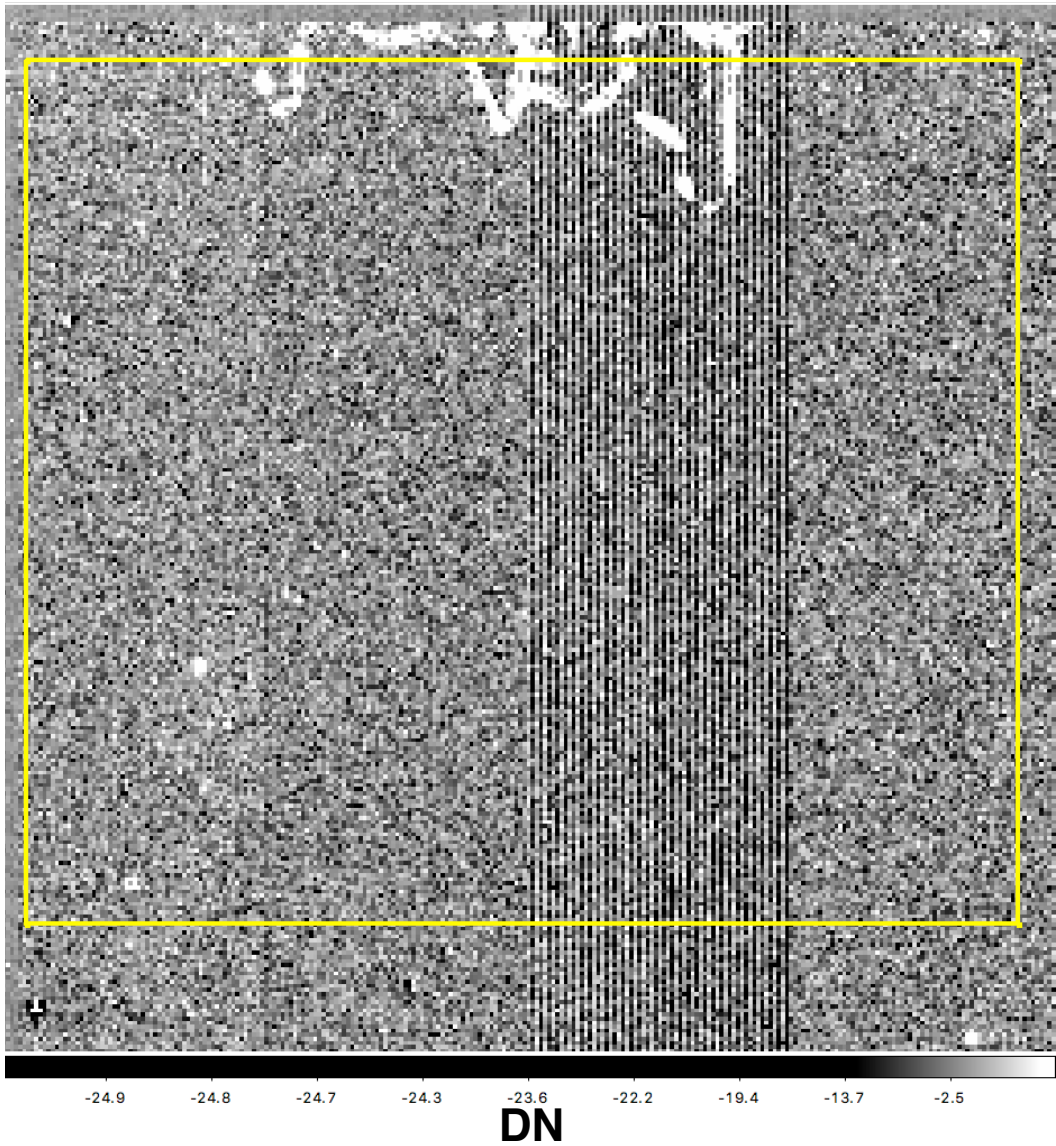


Gauss smoothed 16x16



Zooming in on the alternating column noise





- Alternating column noise aries from how the HxRG columns are read out (*i.e.,* it is a known feature of the HxRG architecture)
- HxRG readout patterns exist that can be used to take this out if necessary. The most common readout pattern, as seen here, leaves it in. If taking it out is important, this needs to be written into the requirements

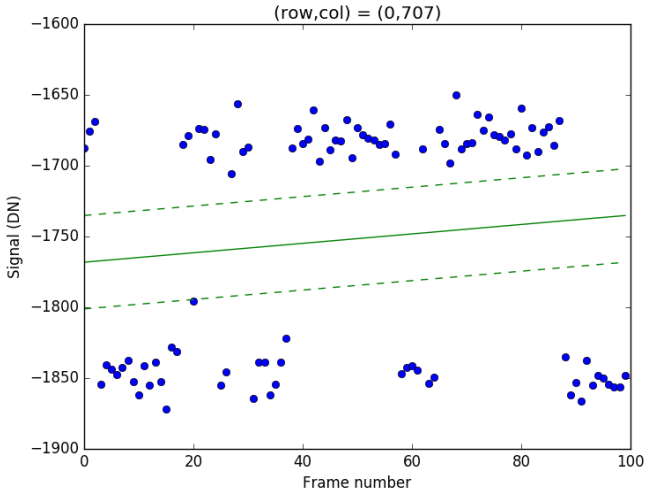
Thoughts on Total Noise

- Based on these data, the read noise is pretty white
- More up-the-ramp samples (200 kHz readout) likely to improve noise
  - This would impact power dissipation and onboard data rates
- **Optimal filters to optimize the system video bandwidth for astronomical scenes should reduce read noise and may be lower impact than high speed readout**
  - What is Fourier transform of the WFI PSF as sampled by the WFI focal plane?
  - Electronic bandwidth should be matched to this. Probably less bandwidth and lower noise than now
  - Trade studies needed to understand benefits of lower noise vs slightly more data loss due to hot and dead pixels
  - Input from FSWG on best figure of merit would be beneficial

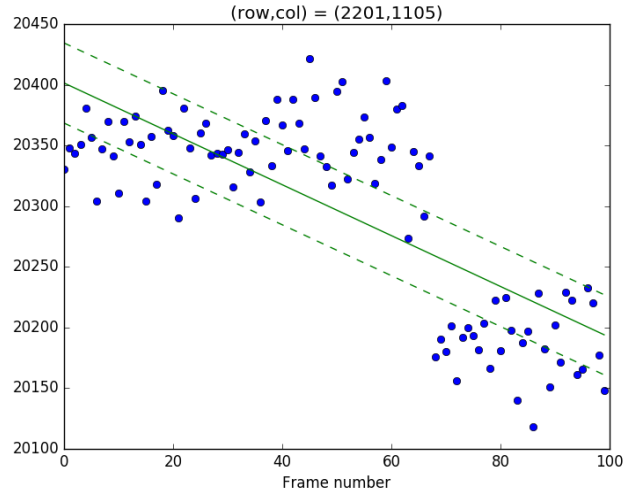
RTN and other Quirky things

RTN in the ≥3σ outliers

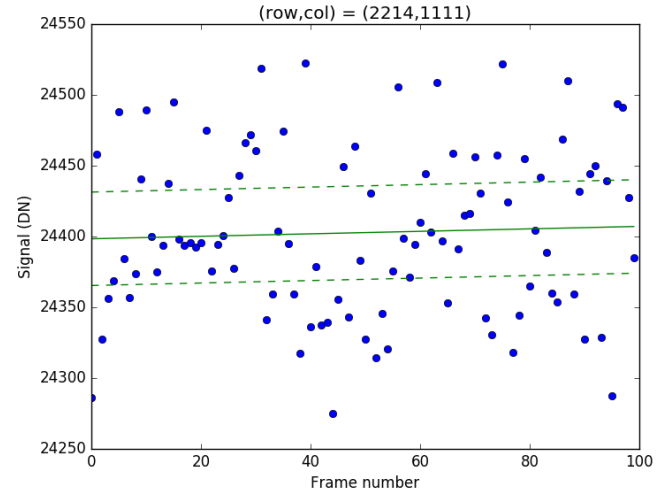
Classic RTN



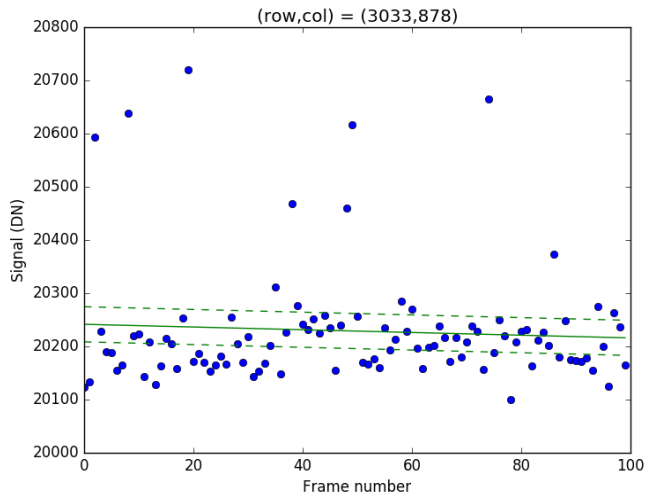
RTN or RTN + a cosmic ray in ROIC?



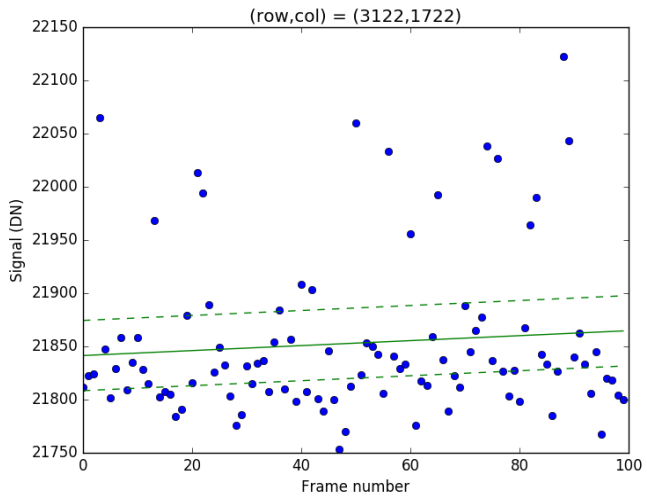
Sticky RTN?



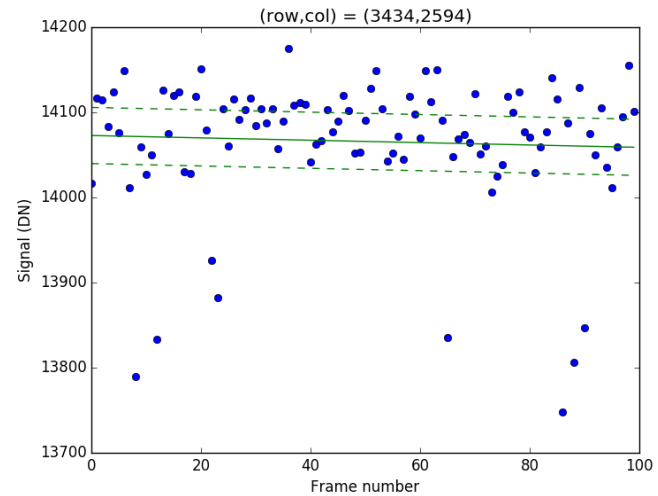
Mostly low



Another mostly low



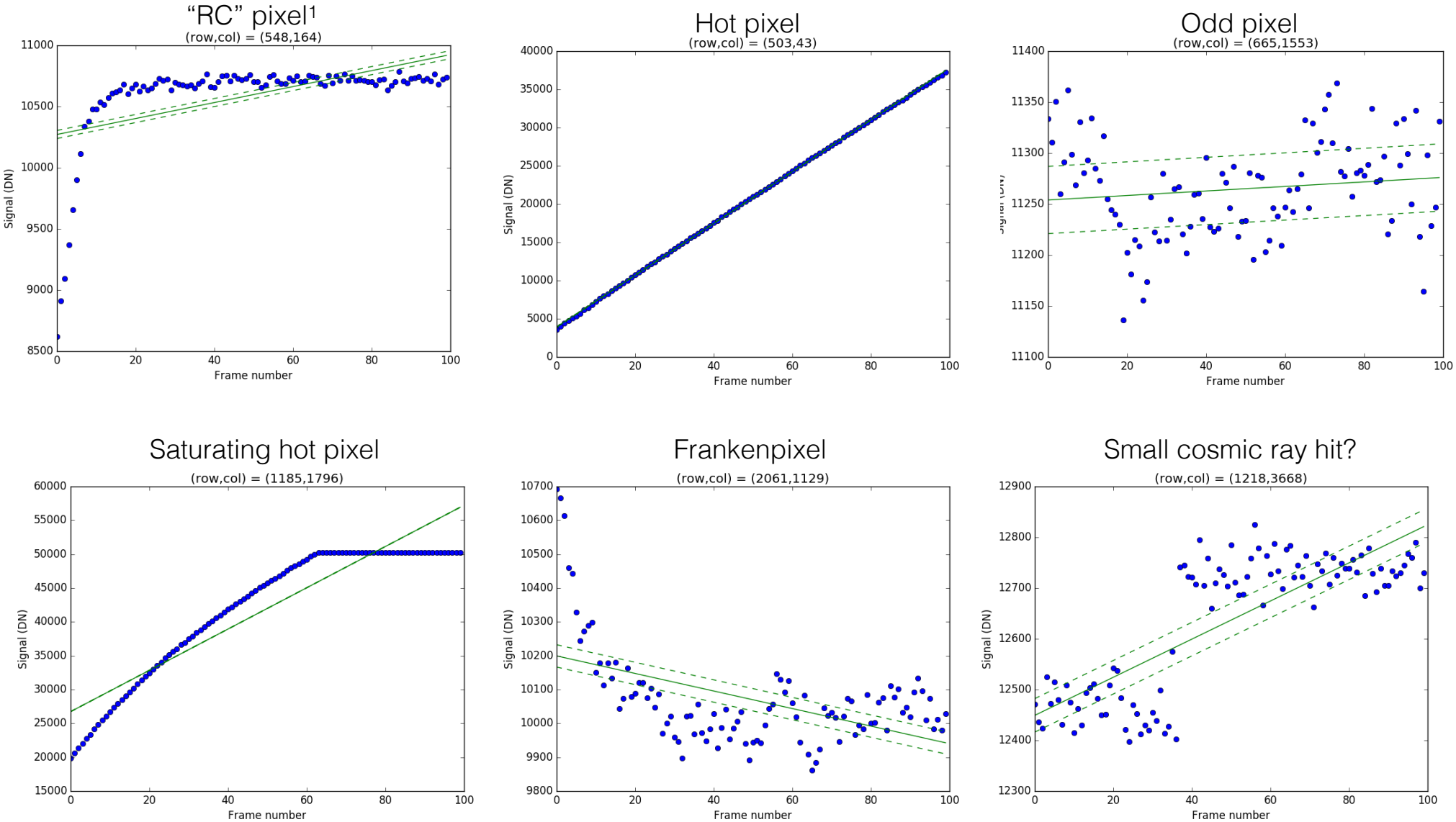
Mostly high



- Qualitative impression is that amount of RTN is in-family with other HxRG detectors, ~few percent of pixels affected. Don't know if they are always the same or not yet. Anticipating the answer will be yes, always the same pixels.
- May be challenging to find in an automated way on account of comparatively high ~15 e^- rms per read noise

Green lines are +/- 1 rms computed across the full data set

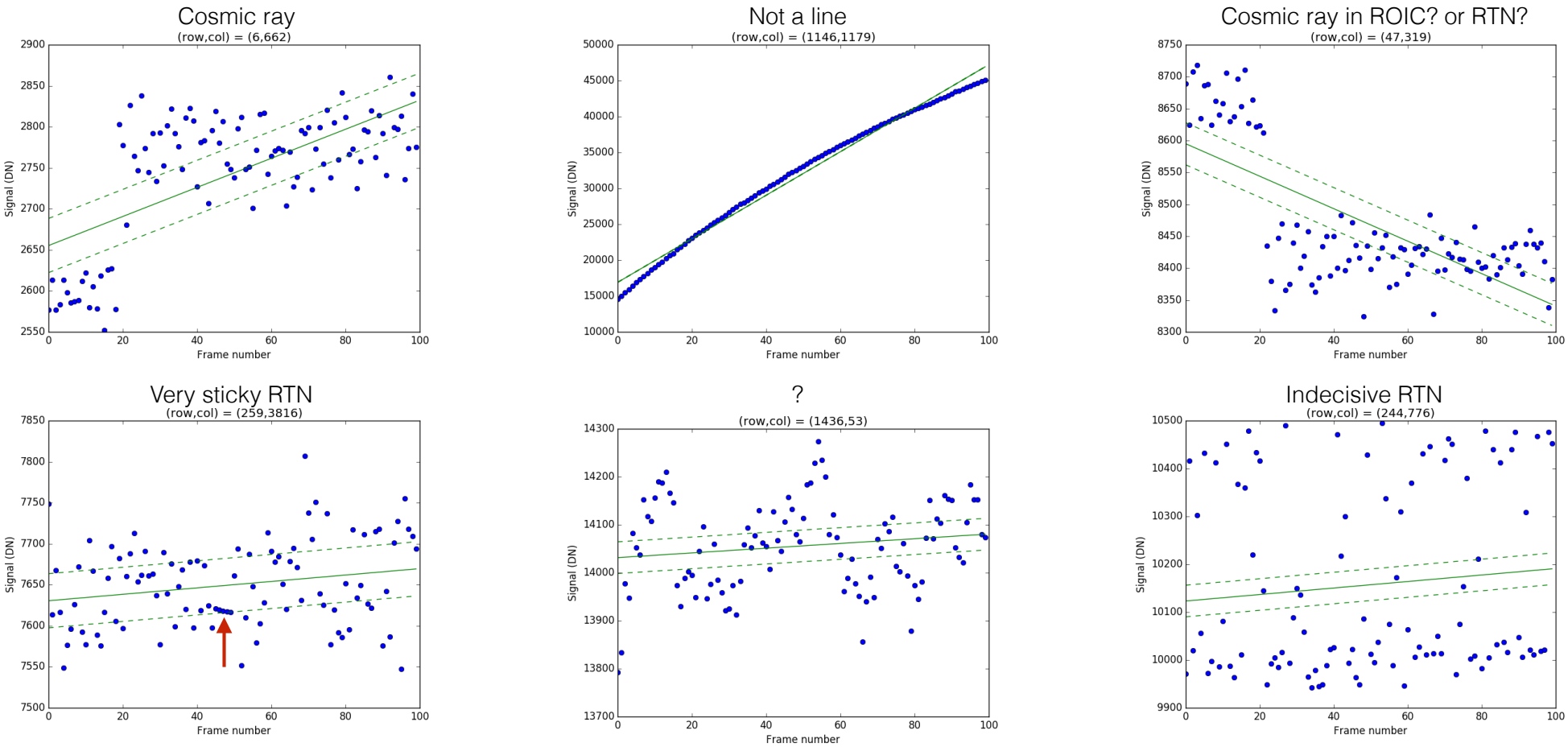
Other quirks in the ≥3σ outliers



- ~3.5% of pixel are ≥3σ outliers. Distribution not chi-square

[1]Only a very small percentage of pixels examined showed RC behavior

Quirks in the ≥6σ outliers



- At the "≥6σ" level, cosmic rays start to become abundant
- Fully 0.7% of our pixels are "6σ outliers". The distribution is clearly not a chi-square
- Not unusual to find quirky pixels like these in HgCdTe HxRGs
- For JWST NIRSpec, for now the plan is to mark the ~few percent of pixels that show RTN as bad. In the JWST H2RGs, individual pixels seem to show RTN or they do not. It is not something that changes from exposure to exposure (although we should verify this for WFIRST)

Things to look into further…

- Have not started to look into the response to light yet (still “to do”)…
- What is the noise power spectrum, for one pixel, sampling up the ramp?
  - May be useful mostly for system optimization, but good to know
  - Requires many darks, all the same
- What is the noise power spectrum of the time ordered pixels?
  - Need to write the software for this
  - Need many darks, all the same
- What is the functional form of the linearity correction?
  - Need many identical illuminated exposures spanning a wide range of flux, fluence, and color.
  - Characterization requirements need to capture: (1) min/max fluxes of interest, (2) min/max fluences of interest, (3) colors of interest, (4) desired parameterization, (5) acceptable uncertainties, (6) ???
  - Need matching darks
- What is the optimal video filter for reducing read noise?
  - (I think) needs to be implemented in hardware for practical readout rates
  - Need PSF model in WFI focal plane
  - Need input from FSWG on figures of merit
- Do any of these things require action? For example, is alternating column noise a problem for the WL surveys? If so, we need to capture it in the requirements

Summary

- Based on a quick look at the sample data, H4RG-17940 seems to be a very good detector
- DCL data are very clean, no obvious test artifacts
- Nothing atypical of HxRGs noted in the electrical or optical behavior for darks so far
- Read noise is a bit high, but can potentially be reduced with
  - Conversion gain computed using lower flux
  - Higher speed readout
  - Matching video bandwidth to WFI system (hypothesized)
- FSWG should think about
  - Do we need a requirement on alternating column pattern noise?
  - Do we need a requirement on the number of allowable RTN pixels, or should this just be factored into the operability requirements (probably my preference)?
  - Linearity parameterization

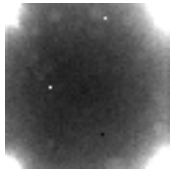
Known Unknowns

A probably incomplete rundown of past “features”

Page (1): Historic “features”

STATUS

Amplifier Glow



A pattern of light, due to the reaout amplifiers, that is highest in the corners and decreases towards the center of the detector

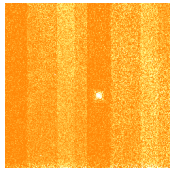
This was fixed with the H2RG. The fix included shielding layers in the H2RG ROIC. There have been reports that a different glow pattern exists in WFIRST H4RG-10s. I did not detect significant glow in the sample data. For now, WFIRST may not or may see this (TBC)

Bad ('Photometrically Challenged') Central Column

The central row/column of apparent decreased sensitivity

This artifact of the NICMOS readout electronics should not affect WFIRST

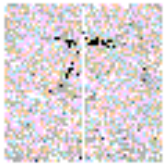
Bias Jumps (Bands)



Wide bands (tens of pixels across) of fluctuating bias levels

This artifact of the NICMOS readout electronics should not affect WFIRST

Cosmic Ray Persistence



Spatially correlated persistent images from cosmic ray hits incurred during SAA passages

This artifact of how NICMOS was operated during SAA passage should not affect WFIRST

✖ Not expected for WFIRST

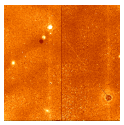
✔ Don’t be surprised…

Source: NICMOS anomalies page
http://www.stsci.edu/hst/nicmos/performance/anomalies/

Page (2): Historic “features”

STATUS

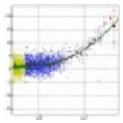
✔ Cosmic Rays



Possible effects of very energetic cosmic ray hits

We should plan to see the occasional atypical cosmic ray event. The details will probably differ from NICMOS’s experience

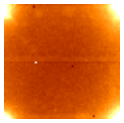
✔ Count-rate Non-Linearity



NICMOS Count-rate Dependent Non-linearity

Also known as “reciprocity failure”. I am hopeful that we will see less pronounced behavior than NICMOS did, but we should plan to see some form of reciprocity failure.

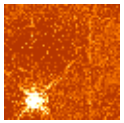
✔ Dark Current



The linear component of the NICMOS dark current

I think this is position dependent dark current. Dark current will depend on position for WFIRST too. The details, however, will differ from NICMOS.

✖ Electronic Bars



Narrow stripes (a few pixels across) occurring at corresponding positions in all four quadrants

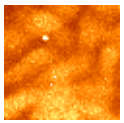
This artifact of the NICMOS readout electronics should not affect WFIRST

✖ ✔ Electronic Ghosts
(Mr. Staypuft, Ringing & Streaking)

Electronic ghost images and bands appearing at points in the other three quadrants which correspond to the position of a bright source in one quadrant

This artifact of the NICMOS readout system should not affect WFIRST. But, careful system engineering is needed to ensure that something similar does not creep back (hence my “no/yet” indication)

✔ Flat Fields



Sensitivity patterns for all three NICMOS cameras

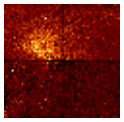
WFIRST flat fields will depend on color and position. Expect to see only very weak fringing (if at all) in substrate removed HgCdTe

Source: NICMOS anomalies page
http://www.stsci.edu/hst/nicmos/performance/anomalies/

Page (3): Historic “features”

STATUS

✖ High Noise Region



Sensitivity variations resulting in noise modulations across the detector

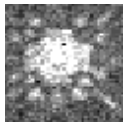
We should not see this artifact that is ultimately thought to trace to large sensitivity variations across the detector. Recent detectors are much more uniform.

✔ Hot and Cold Pixels

Pixels with abnormally high or low sensitivities

We should plan to see inoperable pixels that appear “hot” and “cold”. We should also expect to see “open” pixels.

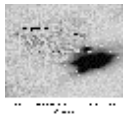
✔ Image Persistence



Excess dark current observed immediately after the observation of a bright target

We should plan to see persistence. The details can be expected to differ greatly from NICMOS

✖ Optical Ghosts



Optical ghosts in the NIC1 polarizers

Not thought to be detector artifact

✖ Particulate Contaminates (GROT)

Small spots of reduced sensitivity, generally extending only over a pixel or two

Not thought to be detector artifact

✖✔ Residual Bias (Pedestal)

A DC offset which remains in an image after the dark current has been removed, producing an inverse flat field pattern in calibrated data

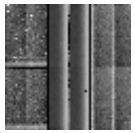
I have indicated “yes/no” because this can be strongly affected by system engineering. Ultimately caused by environmental disturbance, this is not a detector artifact but rather a consequence of how the detector is operated. The details will differ from NICMOS

Source: NICMOS anomalies page
http://www.stsci.edu/hst/nicmos/performance/anomalies/

Page (4): Historic “features”

STATUS

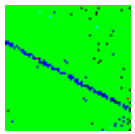
Shading



A time-dependent bias that changes across a quadrant as the pixels are sequentially read out

This artifact of the NICMOS readout electronics should not affect WFIRST

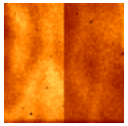
Space Junk



An example of the effects of space junk

Not thought to be detector artifact

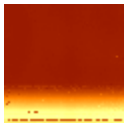
Super Shading



An intermittent phenomenon similar to shading but with an increased amplitude

The NICMOS page does not clearly describe what is thought to cause this, but nothing similar has been seen in extensive JWST testing

Vignetting



A decrease in observed brightness along the bottom edge of all three NICMOS cameras

Not thought to be detector artifact

Intrapixel Sensitivity Variation

“The interpixel sensitivity was found to be an important effect and it varies by as much as 30%.” *Source:* http://www.stsci.edu/hst/nicmos/documents/handbooks/current_NEW/c04_imaging.6.3.html#324873

Effect is **greatly reduced** in more recent HgCdTe. For JWST, the effect is tiny. “Our results indicate that the sensitivity of the detector does not vary across a pixel. The variation we see in the isolated pixel profiles is not a variation in sensitivity, but a redistribution of the signal to neighbouring pixels.”
Source: Hardy, T., Willot, C. & Pazder, J. Intra-pixel response of the new JWST infrared detector arrays. in (eds. Holland, A. D. & Beletic, J.) 9154, 91542D–12 (SPIE, 2014).

Source: NICMOS anomalies page
http://www.stsci.edu/hst/nicmos/performance/anomalies/

From WFC3 detector system

Page (5): Historic "features"

STATUS

✔ **Dark Current Tail**

The dark current behavior of the pixels in the IR detector cannot be completely described by a single number. The distribution of dark current values across the detector is a skewed Gaussian, with a tail of high dark current pixels. The dark current distribution of the IR flight detector will be characterized in the upcoming TV3 testing.

Plan to see non-gaussian dark current histograms

✔ **Inter-Pixel Capacitance**

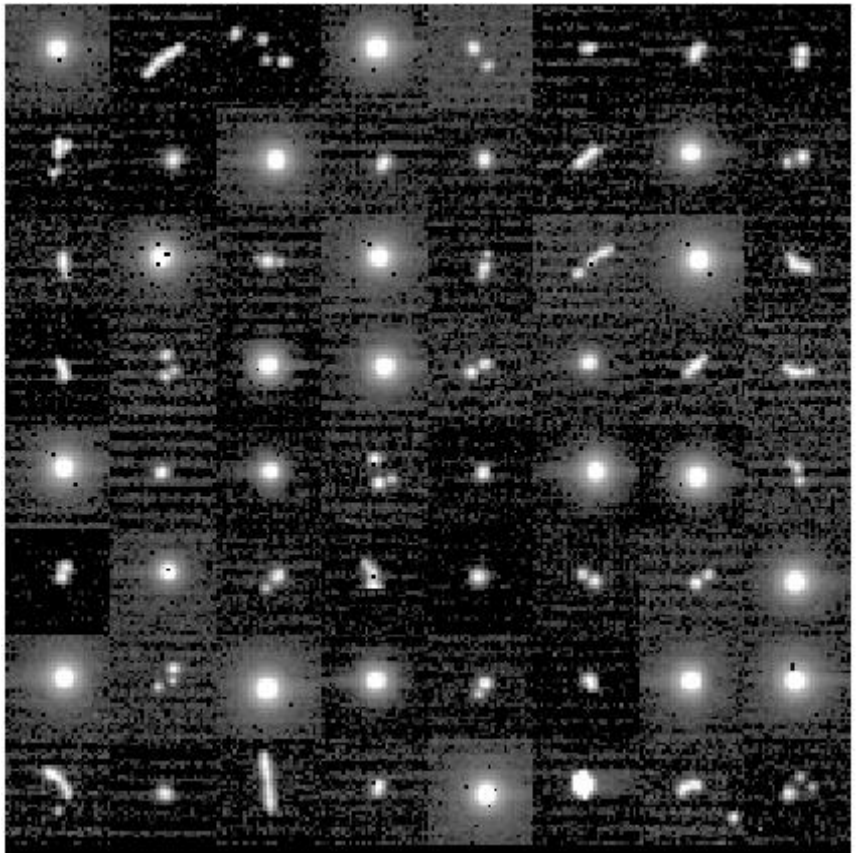
The IR channel is affected by inter-pixel capacitance (IPC), in which the signal measured by one pixel is felt by its neighbors, resulting in an over-production of electrons. This can be thought of as an artificial increase in QE of the detector. From ground testing, we have determined that the effects of IPC can be removed by scaling the measured signal downward by a factor of 0.88. This correction will be implemented in CALWF3.

Plan to see IPC. In the sample detector, the amplitude is more like WFC3 than JWST. JWST has somewhat lower IPC.

✔ **Snowballs**

Snowballs are transient events observed in some HgCdTe detectors that occur instantaneously and deposit at least 200,000 electrons in a small area. ~7400 have been identified in the WFC3/IR channel over 5 years' worth of data, the full table of which is available here. For more information, see the following ISRs:

Plan to see snowballs. For JWST detectors, the rate has gone down with time. Not expected to be a significant issue for JWST on orbit



Examples of snowballs from an early JWST H2RG

? **Persistence that comes back** (from John MacKenty at this meeting)

Testing needed to see what the H4RG-10s do…

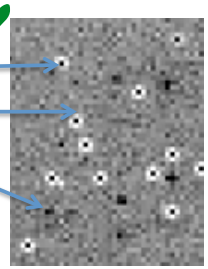
Source: http://www.stsci.edu/hst/wfc3/ins_performance/anomalies/#ssec_ir_darkct

Page (6): Historic “features”

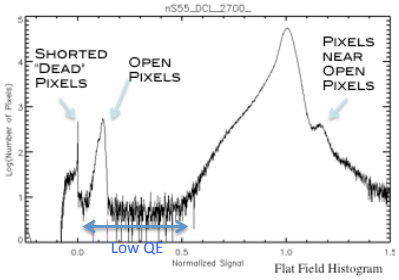
Now from JWST

STATUS

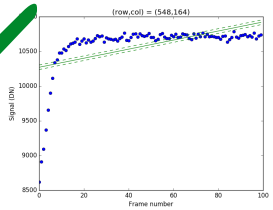
“Open”
“Near open”
“Shorted”



Open , near open, and shorted pixels are apparently not properly connected to the ROIC. Lacking a well defined potential well, charges can move and be collected in neighbors



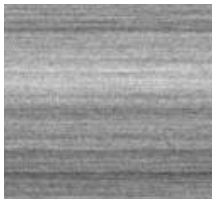
Plan to see similar effects in WFIRST, although WFIRST may differ in the details.



RC pixels seem to only partially reset.

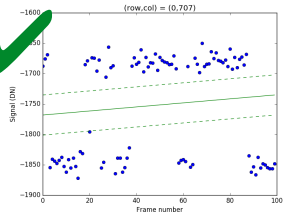
This figure is from the example WFIRST data. Only a very small percentage of pixels appears to be affected

?



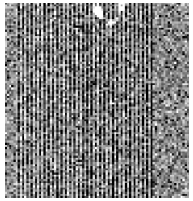
1/*f* noise (banding) from SIDECAR ASIC

Plan to see this if same generation SIDECAR as JWST is used for WFIRST. Hope for a fix if a different sensor chip electronics (SCE) is used



Random Telegraph Noise/Random Telegraph Signal (RTN or RTS)

Plan to see RTN. Based on a quick look, RTN may affect a ~few percent of WFIRST pixels. More study needed.



Alternating column pattern noise

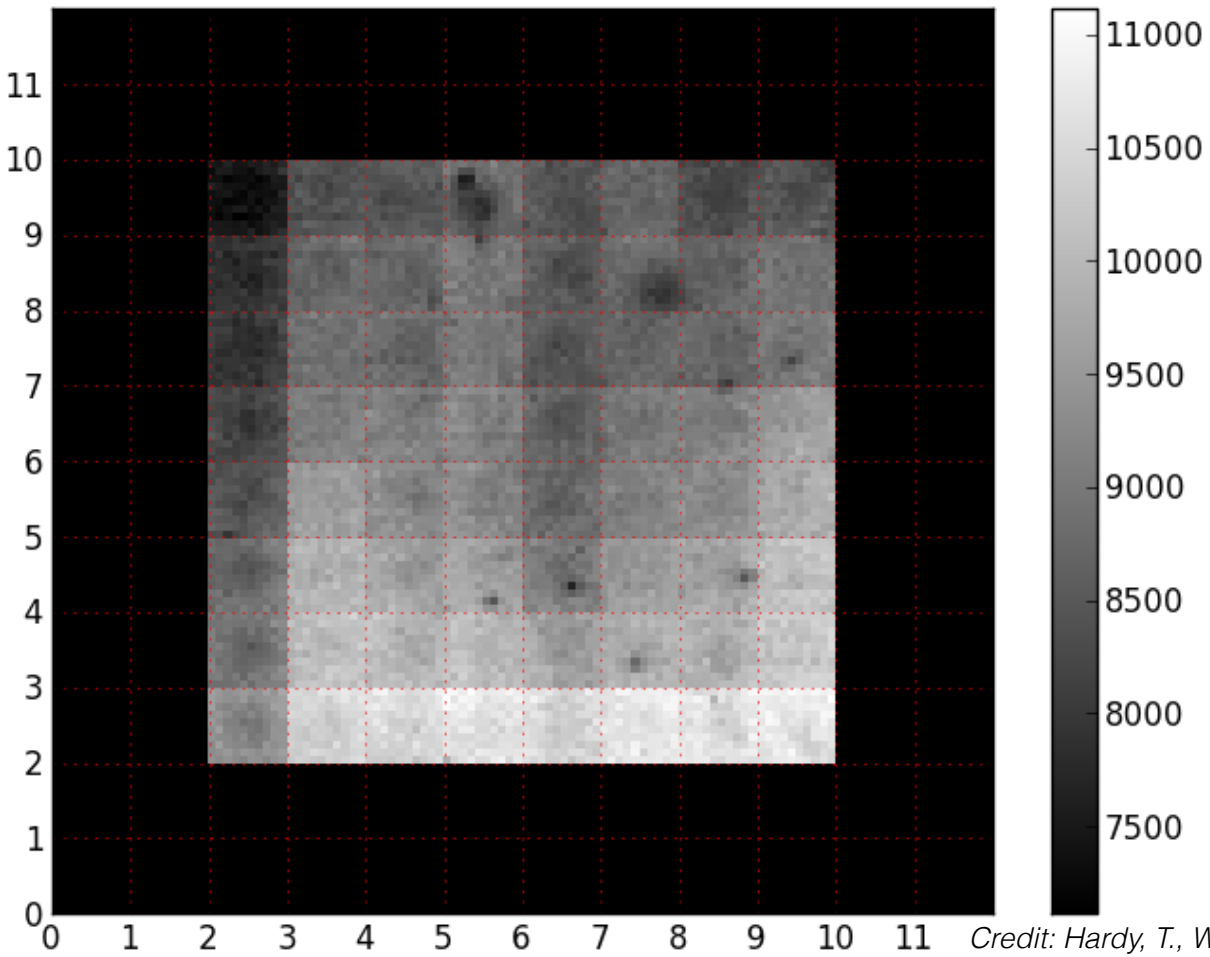
Plan to see this known feature of the HxRG ROIC in WFIRST data

Page (7): Historic “features”

STATUS

Noted for JWST and no reason not to expect it in WFIRST

Pixel Personalities: unique sensitivity structure in individual pixels. Differs from IPS, for which all pixels have similar structure



λ = 650 nm, 8x8 pixels

Credit: Hardy, T., Willot, C. & Pazder, J. Intra-pixel response of the new JWST infrared detector arrays. in (eds. Holland, A. D. & Beletic, J.) 9154, 91542D–12 (SPIE, 2014).

Now from Euclid/WFIRST

Increased persistence upon saturation

See Bob Hill’s charts

Potential Future "Features"

(not noted yet, but may be)

Hypothetical Feature	Description	Why?
Brighter-fatter	PSF shape could be a function of integrated charge. More integrated charge might cause wider PSFs. Brighter-fatter already observed in CCDs	There are no "walls" between pixels. As potential wells (pixels) fill, new charges will be attracted to less full neighbors
Asymmetric charge diffusion	The WFI's charge diffusion PSF may not be symmetric. Risk of greater charge diffusion on the "tilted away" side of the focal plane	The WFI focal plane is tilted with respect to the chief ray. Since momentum is conserved when a photon interacts with the HgCdTe, I would expect to see charge diffusion favor the "tilted away" direction. Hopefully this will be too small to measure…

“Features” Recap & Recommendations

We Should Plan for these

Feature	Recommendation
Cosmic ray hits	Calibration needs to allow for the possibility of cosmic ray disturbance
Count-rate non-linearity (AKA reciprocity failure)	Cap acceptable level in detector subsystem performance requirements. Characterize vs flux, fluence, and color, *etc.* Calibrate.
Position dependent dark current	Include dark subtraction in calibration
Position (and wavelength) dependent flat fields	Include flat fielding in calibration
Hot pixels, cold pixels, open pixels, and near-open pixels	Cap acceptable level in SCA performance requirements. Calibration needs to allow for these kinds of inoperable pixels
Image persistence	Cap acceptable level in SCA performance requirements. Write performance requirement on basis that that persistent pixels are not scientifically useful for a TBD period of time. More characterization and research recommended aimed at recovering persistent pixels more quickly
Non-gaussian dark current distribution	Cap acceptable level in detector subsystem performance requirements. Include dark current subtraction in calibration
Inter-pixel capacitance (IPC)	Cap acceptable level in SCA performance requirements. Characterization and research aimed at reducing effect upon science recommended.
Snowballs	JWST experience is that these will mostly decay away with time (*i.e.* go away and not be a problem)
“RC” pixels	Cap acceptable level in SCA performance requirements.
Random Telegraph Noise/Signal (RTN /RTS)	Cap acceptable level in SCA performance requirements.
Alternating column pattern noise	Cap acceptable level in detector subsystem performance requirements. Good system engineering may reduce impact
Increased persistence upon saturation	Cap acceptable level in detector subsystem performance requirements. More research and characterization recommended
Pixel personalities	No specific recommendations for WFIRST yet other than more characterization would be helpful. Still thinking about best path forward

“Features” Recap & Recommendations

Try to Avoid these…

Feature	Recommendation
Electronic artifacts including ghosts	Cap acceptable level in detector subsystem requirements
Residual bias (pedestal)	Cap acceptable level in detector subsystem requirements
1/f noise (banding)	Cap acceptable level in detector subsystem requirements

“Features” Recap & Recommendations

Research Potential Future “Features”

Feature	Recommendation
Brighter-fatter	More study recommended
Asymmetric charge diffusion	More study recommended