NIRSpec Detectors

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Outline

This talk builds on George Rieke's introduction to infrared detectors, but with an emphasis on NIRSpec

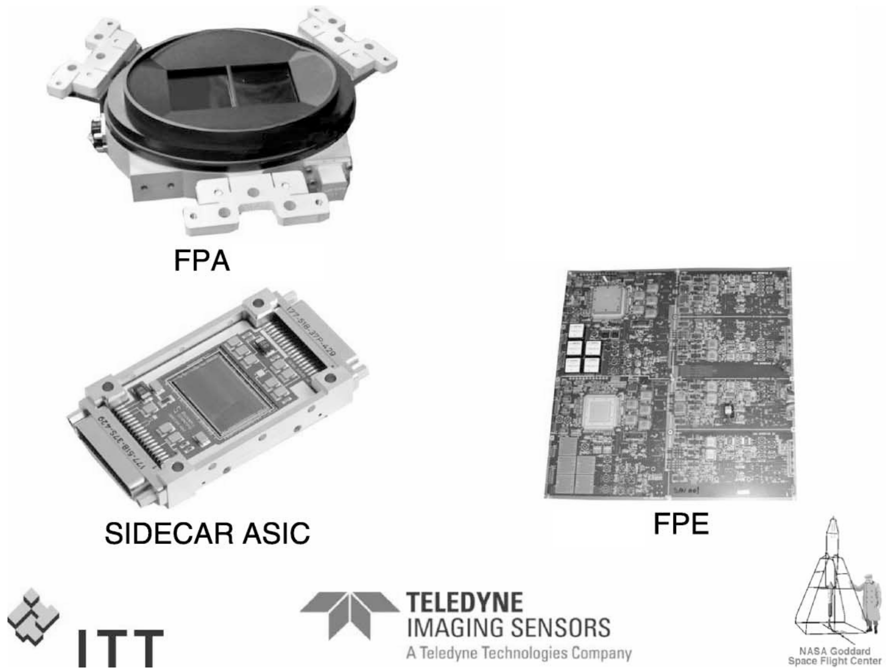
- NIRSpec detector subsystem (DS) hardware
- What the data look like
- NIRSpec detector readout strategy
- How noise scales with readout parameters
- Optimal use of references

NIRSPEC DETECTOR SUBSYSTEM HARDWARE

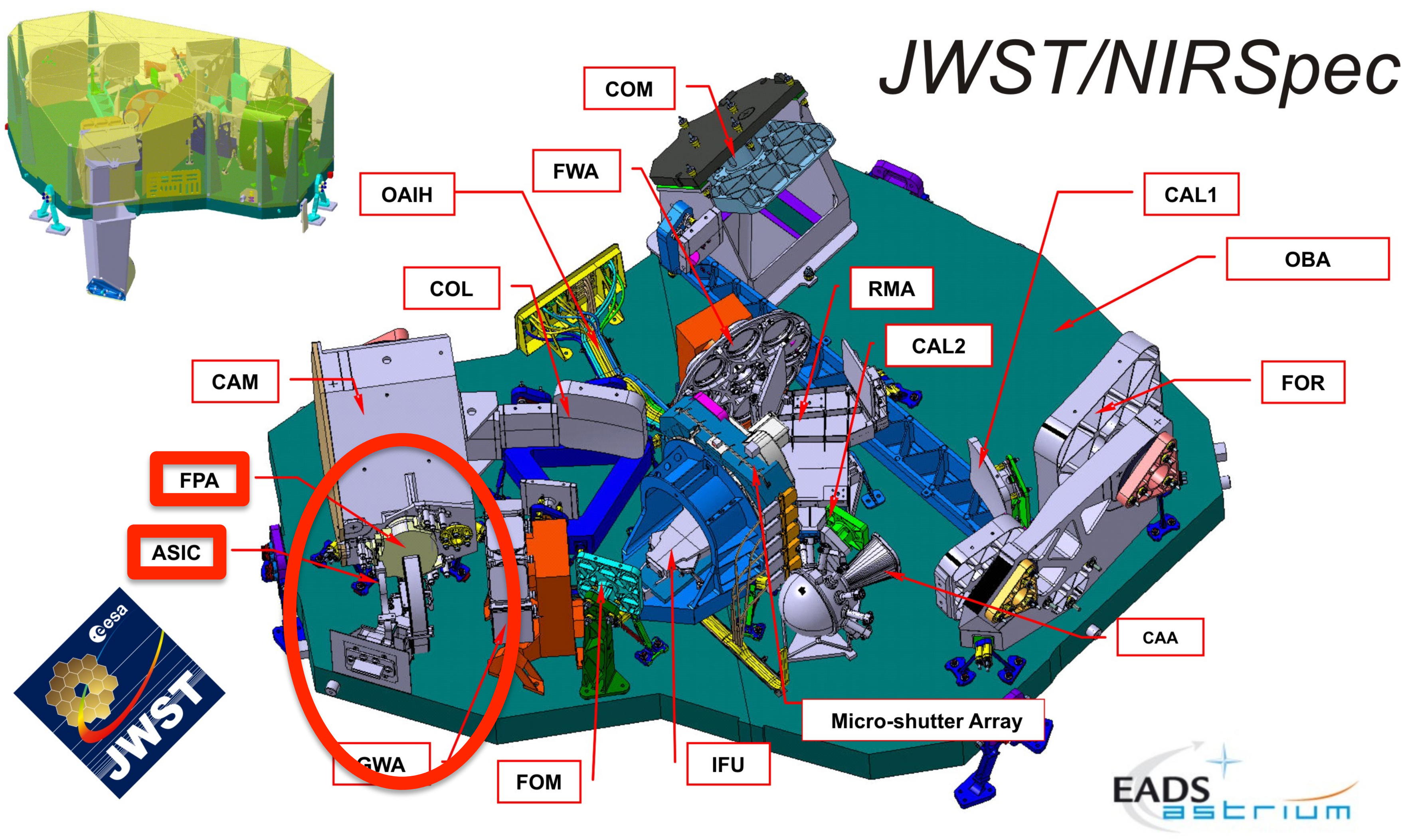
Detector Subsystem: All Components

DS Components

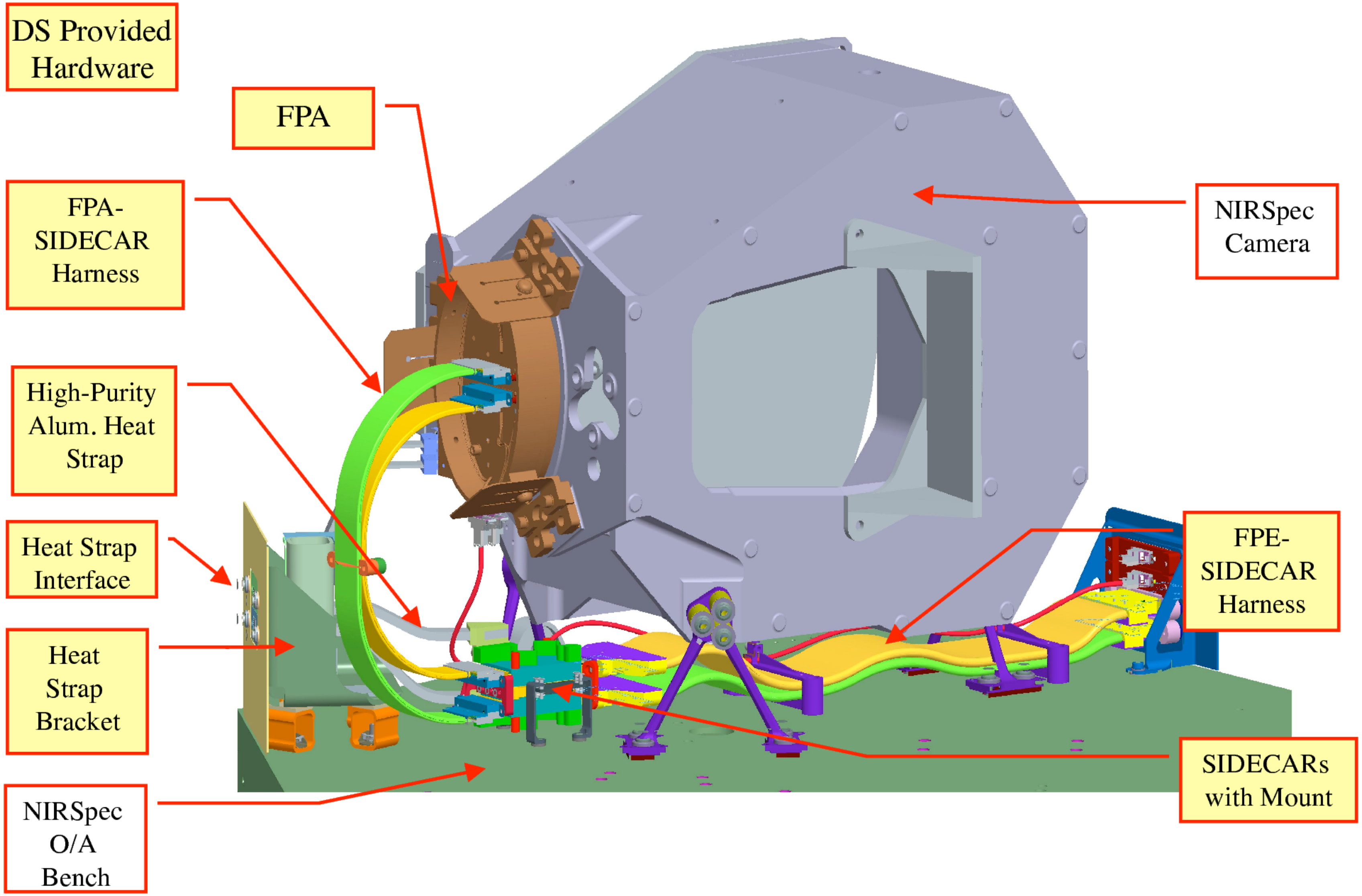
1. The **Focal Plane Assembly** (FPA) detects photons and converts them into electrical voltages. The FPA contains 2 HAWAII-2RG sensor chip assemblies (SCA) –these are the detector arrays
2. The 2 **SIDECAR ASICs** control the FPA and convert electrical voltages from the FPA into digital numbers (DN). These are also known as analog to digital converter units (ADU).
3. The **Focal Plane Electronics** (FPE; this is one box) control the SIDECAR ASICs and interface to the integrated science instruments module (ISIM)
4. There are also electrical harnesses and heat straps for these components that are not shown here



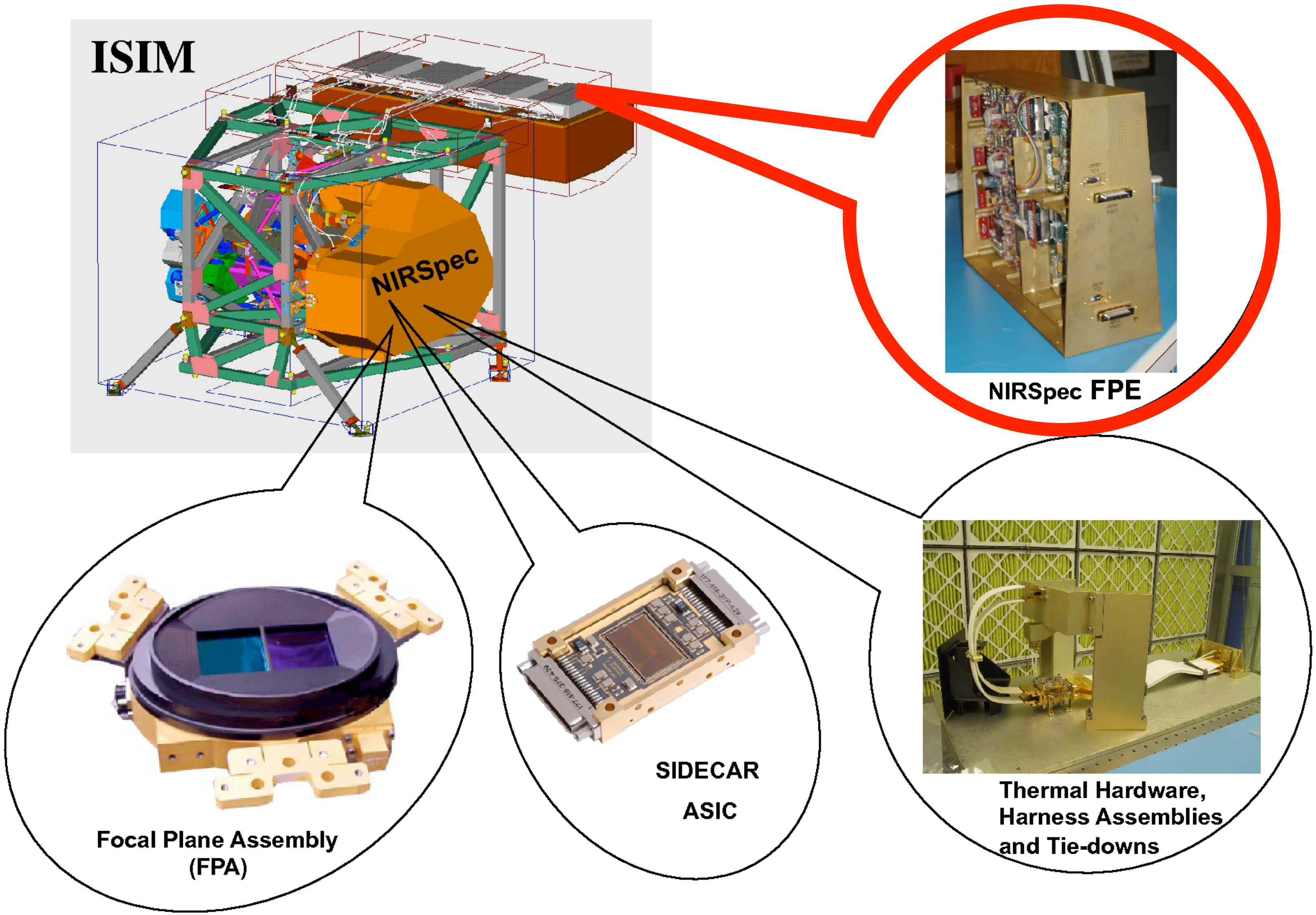
Detector Subsystem: On Optical Bench



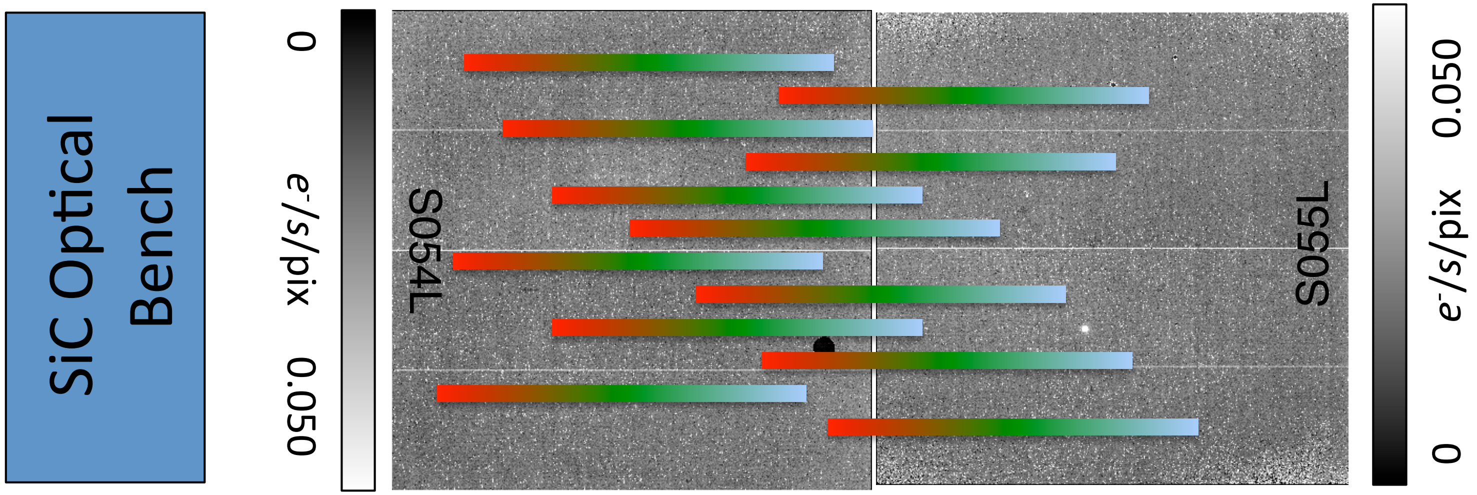
Detector Subsystem: On Optical Bench Detail



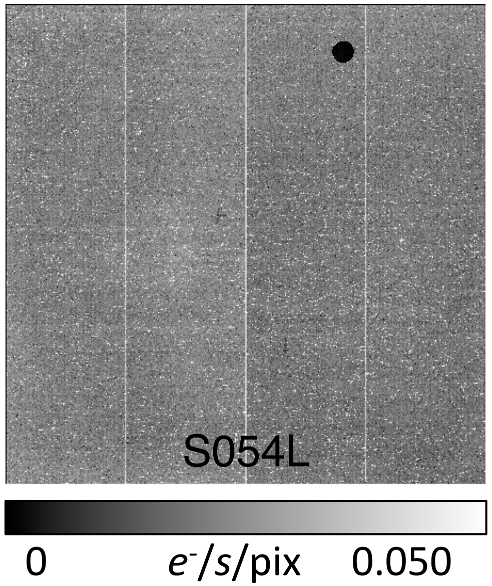
Detector Subsystem (3): In ISIM



What the detector data look like



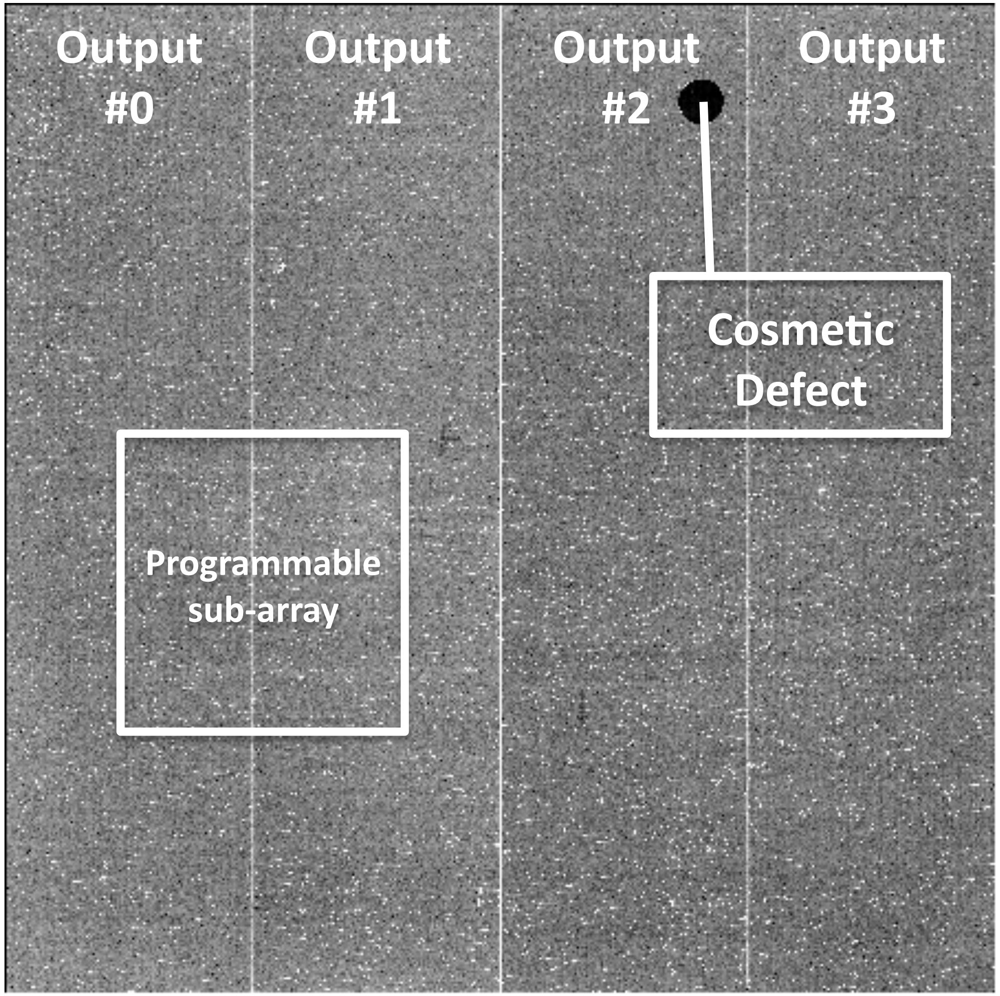
- NIRSpec orients its detectors like this. The view is looking down onto the focal plane. Spectra lie along the slow-scan directions



In the literature, HAWAII-2RG detectors are usually oriented like this

JWST HAWAII-2RG Roadmap

Slow Scan Direction



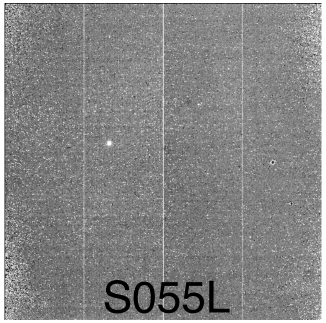
Fast Scan Direction

- JWST H2RGs read out using 4 outputs plus one moveable "sub-array"
- Pixels are continuously clocked at a 100 kHz rate to hold power dissipation constant
- 4-pixel wide border of "reference-pixels" frames 2040x2040 array of photo-sensitive "regular pixels" on all sides
- This technology was developed for flight by NASA, now used by observatories around the world

Summary of key parameters (1)

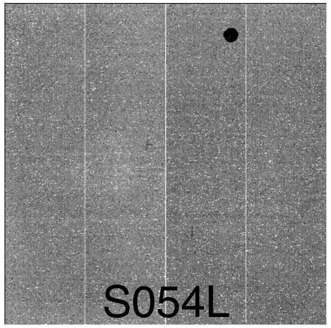
Mean Value for FPA (Weighted by Operability)

Req. #	Test	Required	Measured T = 36.5 K	T = 38.5 K	T = 40 K	Unit	Comment
7.2.1.2	Total Noise per pixel	< 6	6.35	6.35	6.36	e⁻ rms	
7.2.1.3	Mean Dark Current per Pixel	< 0.01	0.0068	0.0074	0.0098	e⁻/s/pixel	
7.2.2.11	Pixel Operability for science observations	> 89 (EOL)	96.90%	96.65%	95.05%		Need 93% BOL



Channel 491

Req. #	Test	Required	Measured T = 36.5 K	T = 38.5 K	T = 40 K	Unit	Comment
7.2.1.2	Total Noise per pixel	< 6	6.62	6.75	6.63	e⁻ rms	
7.2.1.3	Mean Dark Current per Pixel	< 0.01	0.0077	0.0081	0.0103	e⁻/s/pixel	
7.2.2.11	Pixel Operability for science observations	> 89%	95.70%	95.30%	94.60%		Need 93% BOL

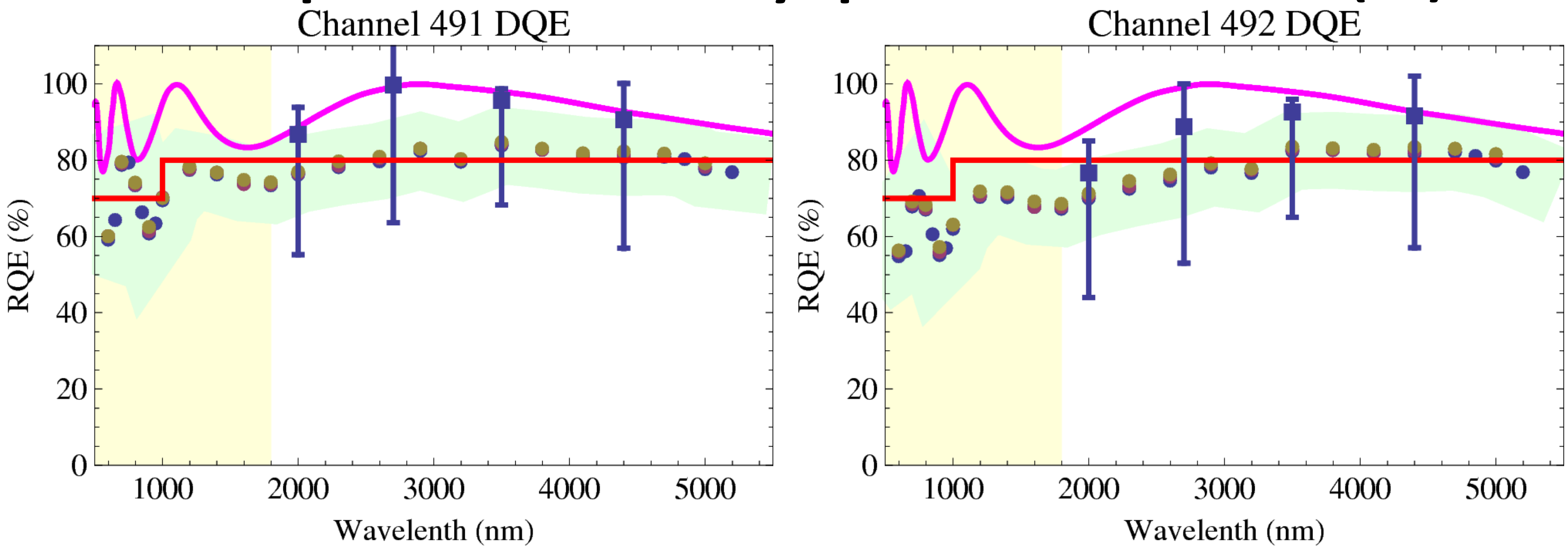


Channel 492

Req. #	Test	Required	Measured T = 36.5 K	T = 38.5 K	T = 40 K	Unit	Comment
7.2.1.2	Total Noise per pixel	< 6	6.08	5.97	6.1	e⁻ rms	
7.2.1.3	Mean Dark Current per Pixel	< 0.01	0.006	0.0067	0.0094	e⁻/s/pixel	
7.2.2.11	Pixel Operability for science observations	> 89%	98.10%	98.00%	95.50%		Need 93% BOL

Preliminary results

Snapshot of key parameters (2)



Measured RQE of NIRSpec FPA S/N104. The color code is: (magenta) measured AR coating at room temperature, (blue box) Teledyne, (blue circle) DCL at $T = 36.5$ K, (purple circle) DCL at $T = 38.5$ K, (gold circle) DCL at $T = 41$ K, (green shading) DCL uncertainty, and (yellow shading) region where the quantum yield is > 1. The DCL uncertainty is probably under-estimated where the quantum yield exceeds unity.

Preliminary results

NIRSPEC DETECTOR READOUT STRATEGY

MULTIACCUM Readout

- Like the other JWST instruments, NIRSpec uses a "MULTIACCUM" readout strategy
  - Uses multiple non-destructive samples up-the-ramp to average down read noise
  - Cosmic ray hits can be detected and corrected for
- Within NIRSpec, often abbreviated to "MULTI-*nxm*"
  - *n* **groups** sampling up-the ramp
  - *m* **frames** averaged together per group
- Baseline full-frame (2048x2048 pixels/SCA) science integration has *n* = 22 & *m* = 4
  - Integration time, INTTIME ≈ 902 *s*
  - Other combinations of *n* and *m* possible
  - Smaller "sub-arrays" of pixels possible

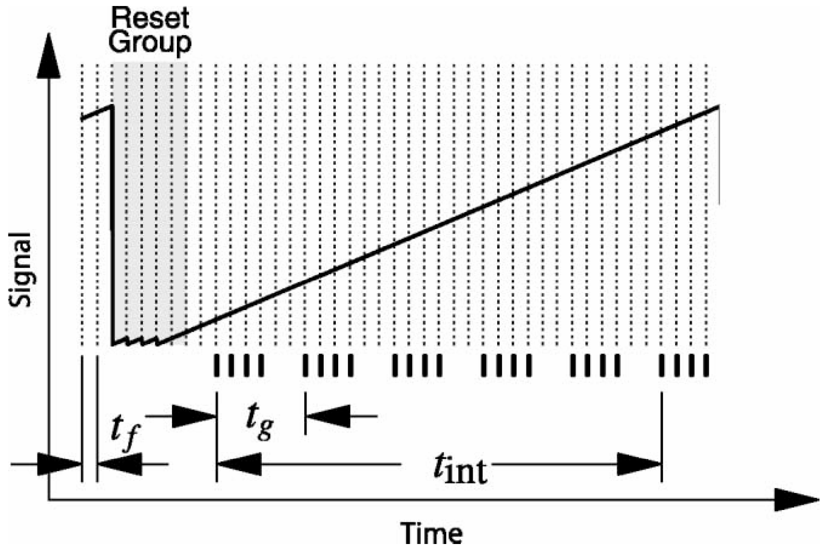


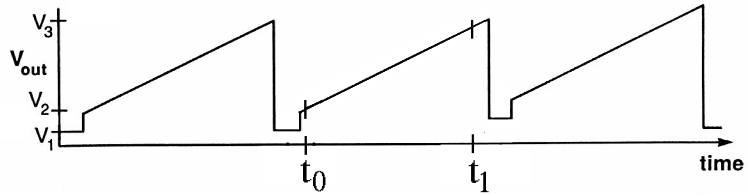
Diagram of the *JWST* NIR detector readout scheme. *JWST*'s NIR detectors use MULTIACCUM sampling. The detector is read out at a constant cadence of one frame every $t_f \approx 10.5$ s. Although frames are clocked and digitized at a constant cadence, to conserve data volume, not all frames are saved. In this figure, saved frames are indicated by short, double-width lines. Likewise, to conserve downlink bandwidth, not all frames are downlinked to the ground. Saved frames are co-added in the FPAP and averaged, resulting in one averaged group of data being saved to the solid-state recorder every t_g seconds. The resulting FITS file, consisting of an up-the-ramp sampled data cube with points spaced at t_g intervals, is downlinked to the ground for further processing.

HOW NOISE SCALES WITH READOUT PARAMETERS

Noise scaling relations

- In George Rieke's lecture, we learned how correlated double samples (CDS) can be used to reject one kind of correlated noise, kTC noise
- By using multiple-non destructive samples at the beginning and end of an integration, we can improve on simple CDS. This is known as "multiple CDS" or "Fowler sampling", after Al Fowler who was one of the first to use this technique with modern near-IR array detectors
- Alternatively, by least-squares fitting a line to up-the-ramp sampled data (i.e. MULTIACCUM), we get the following advantages
  - kTC noise is still rejected
  - Cosmic ray hits can be detected and allowed for in calibration software
  - Noise averages down as many samples are combined
- Depending on how the data are processed, the noise averages down in different ways…

Correlated Double Sampling: CDS



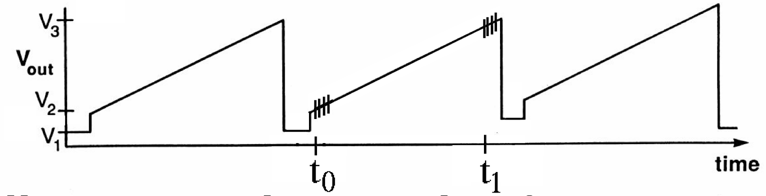
This is a general result

For CDS, one simply adds read noise in quadrature with shot noise on integrated flux,

$$\sigma^2_{\mathrm{CDS}} = 2\,\sigma^2_{\mathrm{read}} + f\,t_{\mathrm{int}}. \quad (1)$$

In this expression, σ_{CDS} is the noise per CDS, σ_{read} is the read noise per read, f is photonic current including flux from the sky and dark current, and t_{int} is integration time. When using this expression, charge must be measured in units of electrons, e^-.

MULTI-CDS or Fowler Sampling



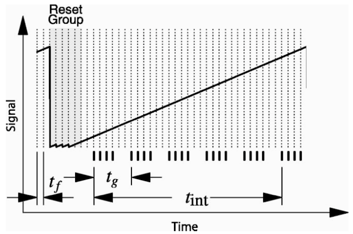
This result only applies when shot noise is small compared to read noise. We present it here because it is frequently seen in the literature.

When correlations in the shot noise are ignored, one simply adds read noise in quadrature with shot noise again. In Fowler sampling, one takes m non-destructive samples at the beginning and m non-destructive samples at the end of the integration. The noise averages down as,

$$\sigma^2_{MCDS} = 2\left(\frac{\sigma_{read}}{\sqrt{m}}\right)^2 + f\,t_{int}, \qquad (2)$$

where we have written the expression to make it explicit that read noise averages down as $1/\sqrt{m}$. The parameter m is known as the "Fowler number". In the litterature, it is fairly standard to represent the Fowler number with the letter n. Here we use m for consistency with the rest of the presentation.

MULTIACCUM Sampling



For up-the-ramp and MULTIACCUM fitting, correlated shot noise is usually important. For this case, we present only the general result.

For up-the-ramp and MULTIACCUM sampling, correlated shot noise is usually important. For this reason, we present only the general result,

$$\sigma^2_{\text{total}} = \frac{12\,(n-1)}{m\,n\,(n+1)}\,\sigma^2_{\text{read}} + \frac{6\,(n^2+1)}{5\,n\,(n+1)}\,(n-1)\,t_g\,f - \frac{2\,(m^2-1)\,(n-1)}{m\,n\,(n+1)}\,t_f\,f. \qquad (3)$$

In Eq. 3 we have introduced the group readout time, t_g, and the frame readout time, t_f. This is a direct result of classical propagation of errors for least-squares line fitting for each pixel, $s = a + b\,t$, where s is integrated signal and b is the slope.

$$\sigma^2_b = \sum_{i=1}^{n\,m}\sum_{j=1}^{n\,m}\frac{\partial b}{\partial s_i}\,\frac{\partial b}{\partial s_j}\,C_{i,j},\ \text{and} \qquad (4)$$

$$\sigma^2_{\text{total}} = (n-1)^2\sum_{i=1}^{n\,m}\sum_{j=1}^{n\,m}\frac{\partial b}{\partial s_i}\,\frac{\partial b}{\partial s_j}\,C_{i,j}. \qquad (5)$$

The covariance between samples $i \neq j$ sampling up-the-ramp is, $C_{i,j} = s_{\min(i,j)}$. For the special case $i = j$, we must add the read noise in quadrature, $C_{i,i} = s_i + \sigma^2_{\text{read}}$. The interested reader is referred to [1] for a complete derivation.

Pierre Ferruit was the first to derive this result.

Caveats

- For both MCDS and MULTIACCUM, the noise does not average down quite as well as is indicated by Eqns. 2-3.
  - The discrepancy is on the order of 10%
- The villain is other correlations that are present in the data.
- For NIRSpec's SIDECAR ASIC based DS, 1/*f* noise originating in the SIDECAR ASIC is the biggest contributor.

Worked Example (p. 1)

It has been deemed that the only long exposures that you are allowed to take use the baseline MULTI-22×4 readout. You want to look at faint sources that have an average flux at the FPA, f_{src} = 0.01 ph/s/pixel *, and are not convinced that MULTI-22×4 is the best thing to do… What full-frame readout mode would be better for your program?*

From the NIRSpec WWW pages, you see that the detectors have about the following parameters in MULTI--22×4 full-frame readout.

$$\sigma_{\text{total}} = 6.35\, e^{-} \text{ rms}$$

$$i_{\text{dark}} = 0.007\, e^{-}/s/\text{pixel}$$

$$\text{QE} \approx 80\,\%$$

$$\text{TFRAME} = 10.74\, s$$

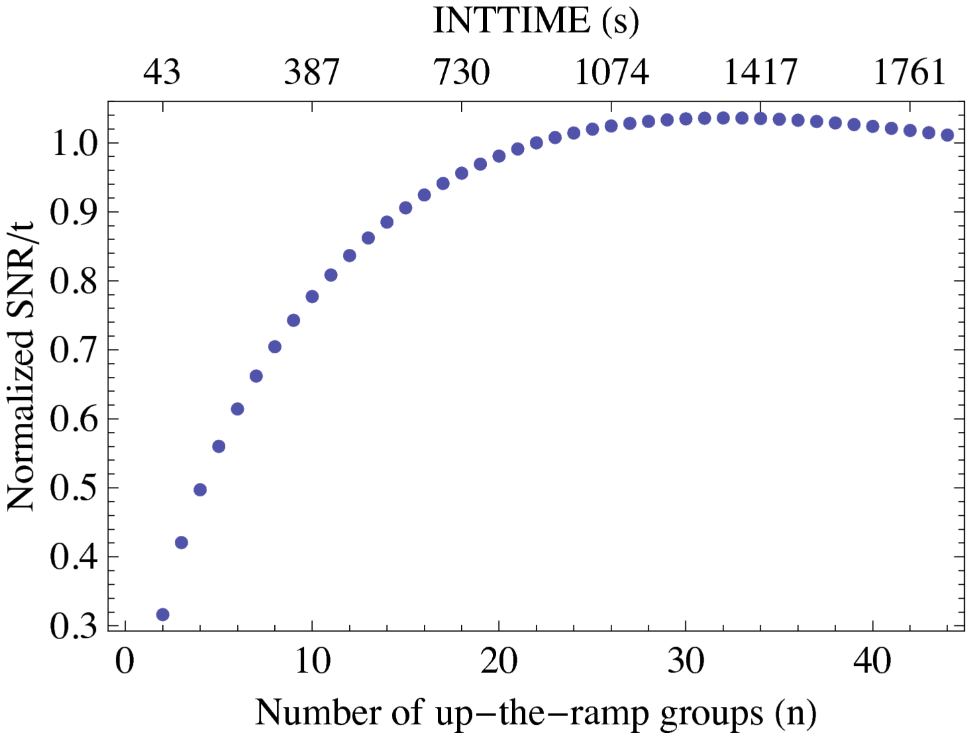
$$\text{TGROUP} = 42.95\, s$$

Using Eq. 3 with $n = 22$ and $m = 4$, you quickly work out that the read noise per read is about $\sigma_{\text{read}} = 16.3\, e^{-}$ rms. After a bit of discussion, you learn that there may be some flexibility on the number of up-the-ramp groups, n, but that you will be required to use $m = 4$ frames per group. Using Eq. 3, you make a plot of the signal-to-noise ratio (SNR) per unit time for different values of n, but with $m = 4$. You therefore plot the following quantity,

Worked Example (p. 2)

$$\frac{\mathrm{SNR}}{t} = K \frac{n-1}{n} (f_{src}\, QE) \times \left(\frac{12\,(n-1)}{m\,n\,(n+1)} \sigma_{read}^2 + \frac{6\,(n^2+1)}{5\,n\,(n+1)} (n-1)\, t_g\, (f_{src} + i_{dark}) - \frac{2\,(m^2-1)\,(n-1)}{m\,n\,(n+1)} t_f\, (f_{src} + i_{dark}) \right)^{-1/2}, \quad (6)$$

with the normalization K chosen so that it has the value 1 for the baseline value, $n = 22$.



Worked Example (p. 3)

- For this example, there is only a small advantage to be gained by using n ~ 30 instead of the baseline n = 22 value
- Moreover, for longer integration times, more pixels will be corrupted by cosmic rays
  - This can be fixed, but at a cost in SNR
- In any case, many co-added integrations will be needed. About 5×10^4 *s* of integration time needed to achieve SNR ~ 7

OPTIMAL USE OF REFERENCES

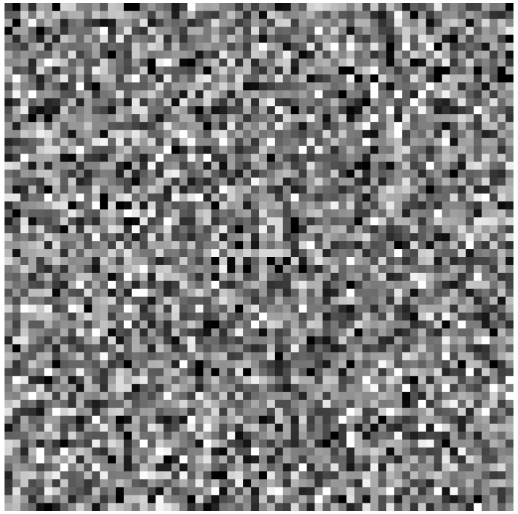
Noise reduction study

- Principal components analysis shows that the total noise reported on chart 10 is dominated by: (1) 1/*f* noise that originates in the SIDECAR ASIC and (2) alternating column pattern noise that originates in the ROIC.
- The 1/*f* noise is correlated in time but not in frequency
  - Best handled in frequency domain (i.e. Fourier space)
- The 1/*f* noise is correlated across all 4 outputs and the reference output (i.e., we have many references available to sample it)
- The baseline JWST H2RG readout modes are far from optimal for 1/*f* noise
  - Reference pixels in the first and last 4 rows much too far away
  - Reference pixels at ends of rows too far away
  - Reference pixels too noisy
- **The good news -total noise can potentially be cut in half by employing well-established IR instrumentation techniques that sample low noise references more frequently to reject 1/*f***
- Doing this will require sending down different data than is currently planned. May also require sending more data for best results.
- Optimized experiments will begin at Goddard shortly after the NIRSpec flight DS ships in a few weeks

1/*f* noise and why it matters

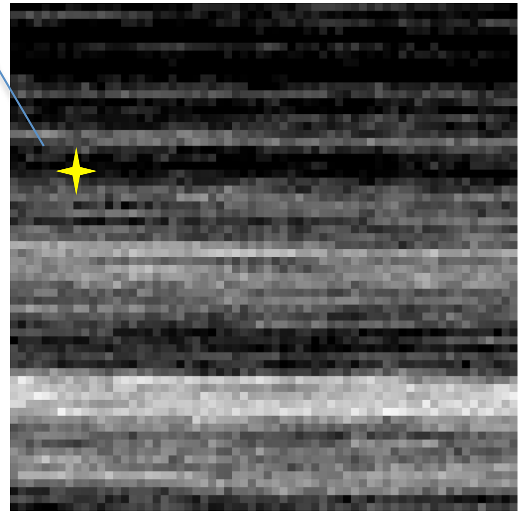
- These 2 images are on the same grayscale and have the same standard deviation, 6 *e-* rms
- Correlated *1/f* noise can cause one to overlook targets, or over-estimate the statistical significance of a detection if it is not handled carefully

Uncorrelated 6 *e-* rms



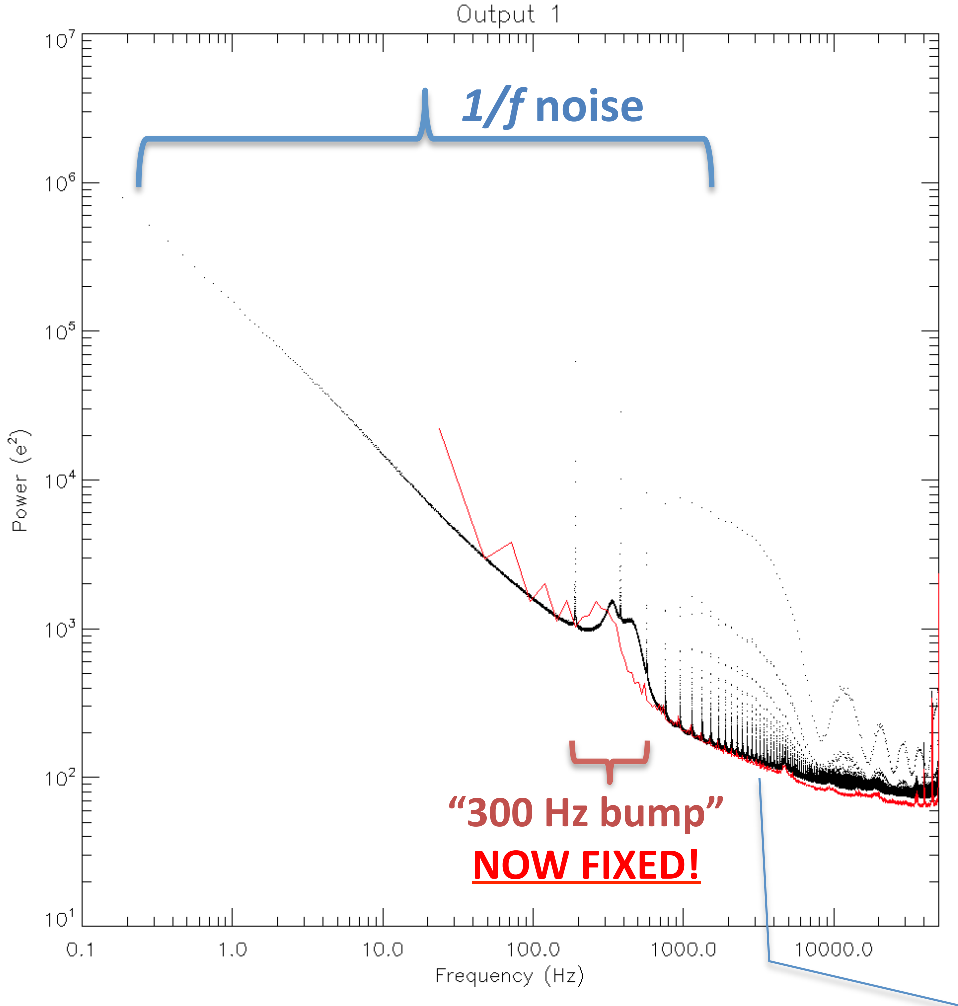
50% *1/f* 6 *e-* rms

Small target located here easy to overlook



- Probability of detecting targets independent of position in array
- Detection probability depends on position unless handled carefully

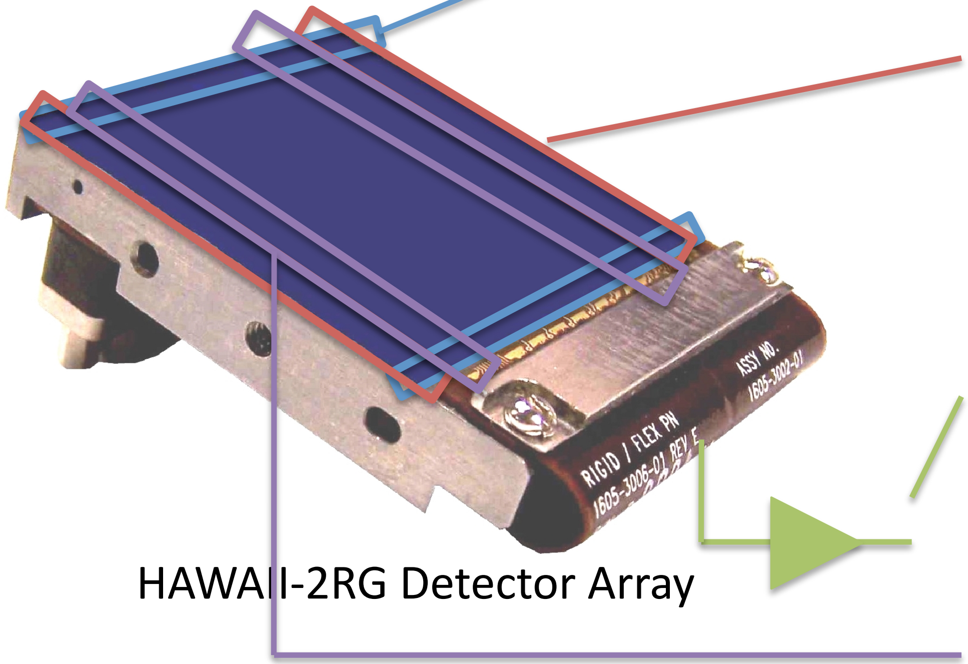
Key to removing 1/f is sampling low-noise references frequently



- By viewing the pixels as a time series, we can Fourier transform the data to construct Fourier noise power spectra
- Consistently reveal 1/*f* with a "knee" at ~5 kHz
- **By sampling low-noise references every 16 pixels or so, can remove 1/*f***

Need to sample at a frequency higher than the "knee", ~few kHz

Many References are Available for NIRSpec



HAWAII-2RG Detector Array

4 rows of ***reference pixels*** along the "bottom" and "top" edges of each detector array

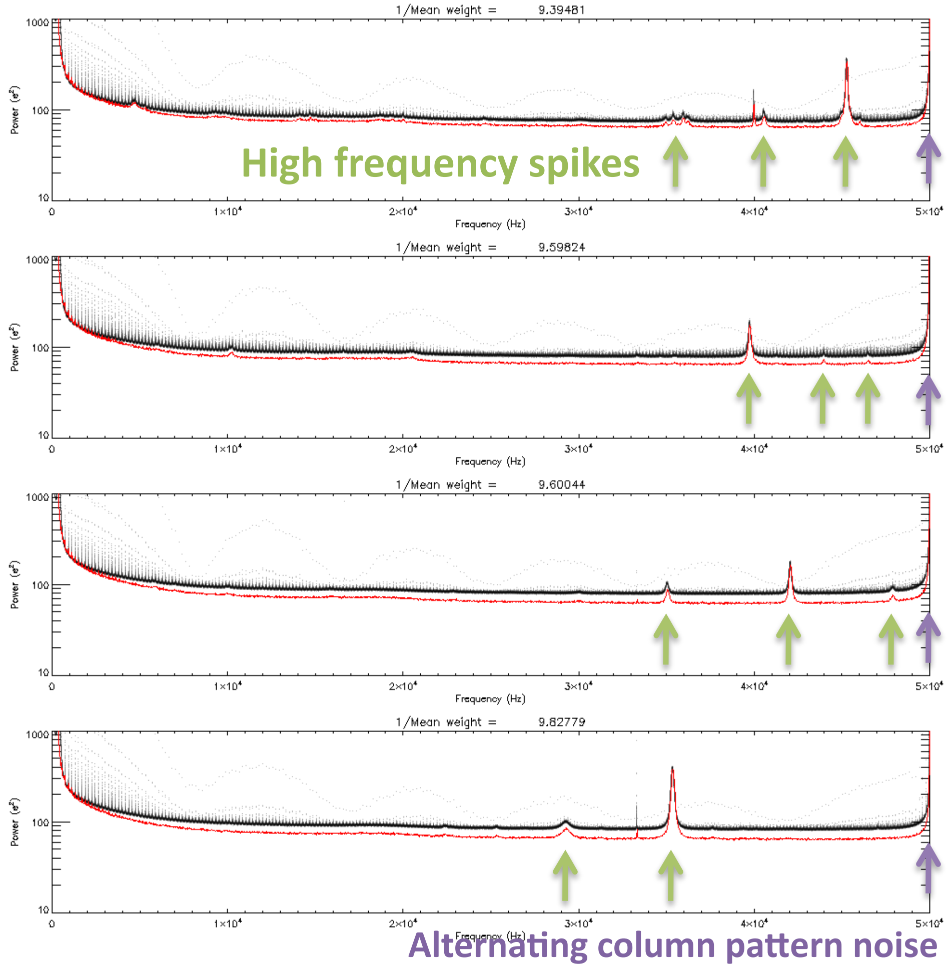
4 columns of ***reference pixels*** along the "left" and "right" edges of each detector array

A separate ***reference output*** that is always available for all pixels

Regular pixels (used as a reference) because they are vignetted and never see light

Results since Feb. 17th, 2010

- So far, the noise reduction team (Arendt, Fixsen, Lindler, Loose, Moseley, & Rauscher) has worked within the constraints of the existing readout patterns to
  1. Eliminate high frequency spikes (at right, now fixed)
  2. Largely eliminate "300 Hz bump"
  3. Implement "frequency dependent reference pixel correction"
- Taken collectively, these improvements reduce the total noise (measured in raw ADU) by about 17% compared to what was achieved before the study began

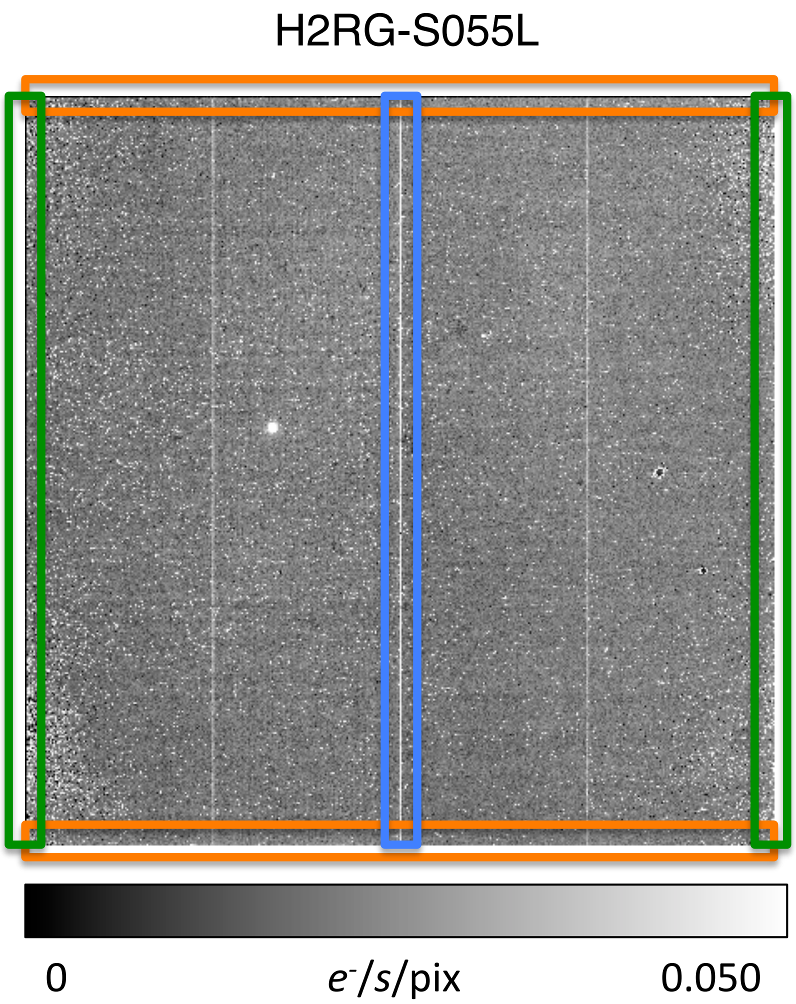


See chart 26 for the "300 Hz bump"

Frequency dependent reference pixel correction

This is an example of what is possible working within the constraint of the existing readout modes. We plan to explore more powerful techniques that use different and more data. For now, however, this example describes some of what is possible if nothing is changed and provides one example of the techniques that we are using.

- HAWAII-2RG SCA has reference
  - In rows
  - In columns
- Reference pixels in rows used to remove DC drifts from output to output
- Reference pixels in columns used to remove 1/*f* noise in frames of data
  - Reference pixels in columns read out at the same time as these regular pixels
- Need to understand the correlation between the blue regular pixel columns and green reference pixel columns.

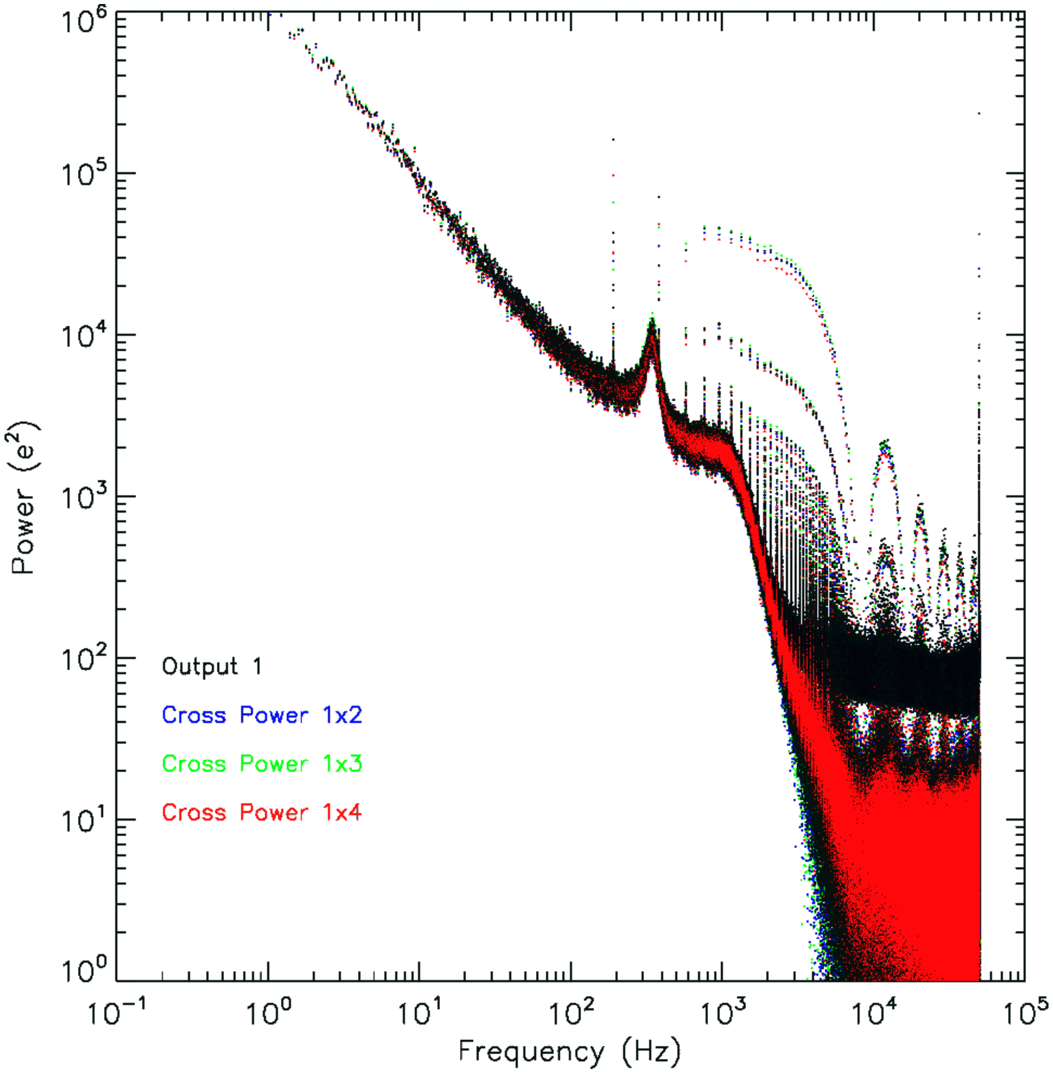


Comparing the power spectra of references and regular pixels

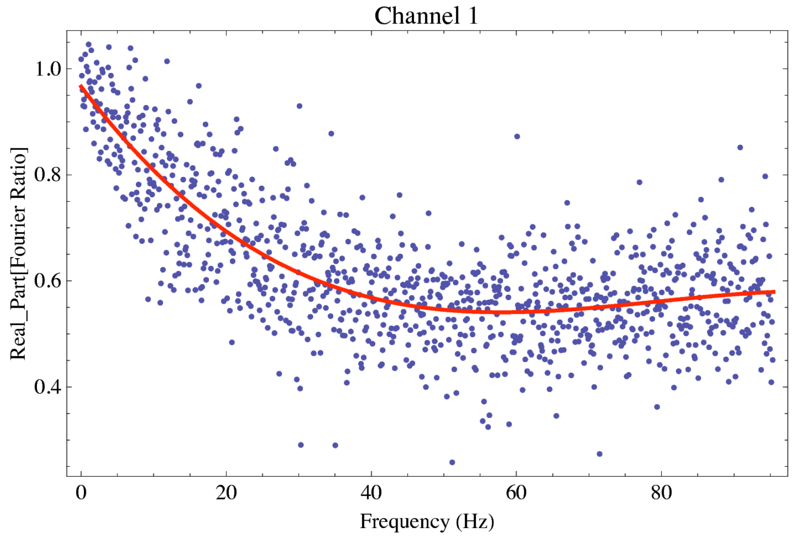
- Used special readout software to return the reference output on output #4
- Computed cross power spectra
- Noise power spectrum

  $$P_{\mathrm{ii}} = \langle \mathcal{F}(Q_i)\, \mathcal{F}^*(Q_i) \rangle$$
- Cross power

  $$P_{\mathrm{ij}} = \langle \mathcal{F}(Q_i)\, \mathcal{F}^*(Q_j) \rangle$$
- 1/f is highly correlated across all outputs and reference output
- Similar result holds for reference pixels
- Plots are right were renormalized to align with the noise power spectrum (black)
- Frequency dependent gain must be applied



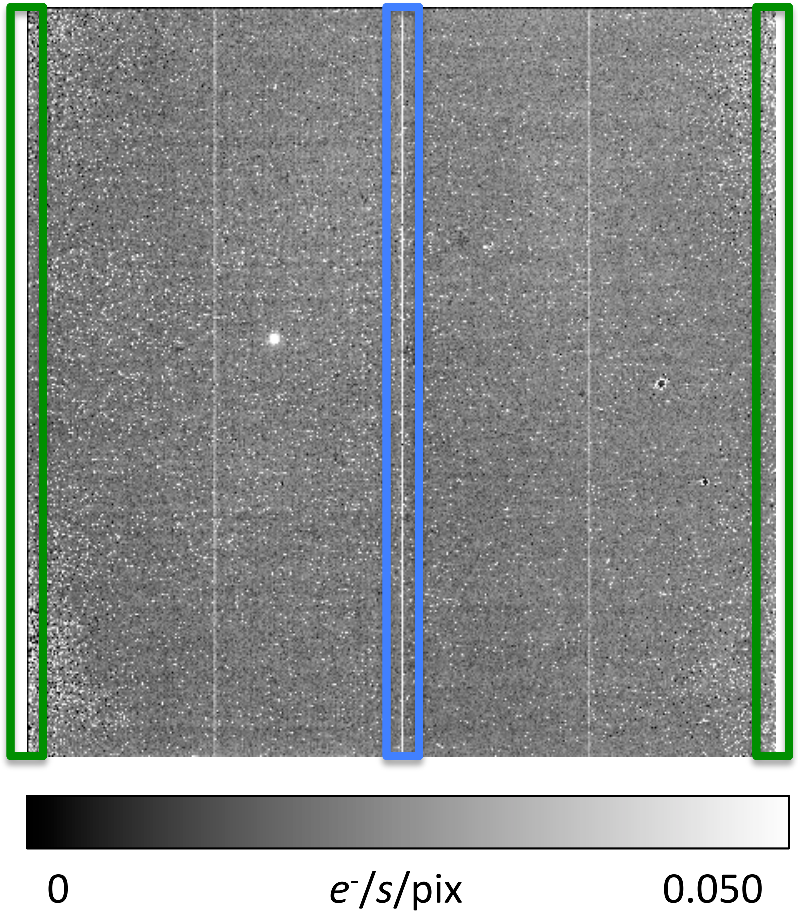
Compute the FFT of (blue) regular columns divided by (green) reference columns & average over lots of data!



Real part of the ratio of the Fourier transorm of regular pixels in columns to reference pixels in columns, $\mathcal{R}$ = `Re[`$\mathcal{F}$`[regpix)]/`$\mathcal{F}$`[refpix]]`. The gain depends on frequency. Although the two channels have somewhat different characteristics, the underlying conclusion that there is frequency dependent gain applies to both.

- The corresponding plot for the imaginary part of the ratio is a scatter plot closely clustered near zero
- No significant phase difference!
- Low pass filtering, as most groups do, is not optimal! Significant correlation exists all the way up to the Nyquist frequency a 100 Hz.
- Moreover, if low pass filtering is implemented as some kind of rolling average, as most groups do, this correlates the noise –which is something that is to be avoided

H2RG-S055L



How do we use the reference pixels?

- Working within the current readout mode constraints, the following is very close to optimal in a least-squares sense
  1. Use the mean of reference pixels in rows to add/subtract a constant from each output to remove DC drifts
  2. After rejecting statistical outliers, compute the FFT of reference pixels in columns
  3. Apply the frequency dependent gain shown on the previous chart
  4. Invert the FFT
  5. Use linear interpolation to compute a reference value for every pixel in the SCA
- Some incremental improvement is still possible, particularly as regards alternating column pattern noise
- Large improvements still possible, and will be explored! by reading out the SCAs differently to provide more and better references

Acknowledgments

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GLOSSARY & REFERENCES

Glossary

Acronym	Definition
ASIC	The SIDECAR ASIC is an **application specific integrated circuit**. It provides electrical biases for, controls, and sequentially reads through pixels in the SCA.
DS	The **detector subsystem** contains the hardware and software that convert photons that enter NIRSpec into digital data.
FPE	The **focal plane electronics** control the SIDECAR ASICs. The FPE are mounted in ISIM, not on the NIRSpec optical bench.
H2RG	Short for **HAWAII-2RG**. HAWAII-2RG is Teledyne Imaging Sensors' trade name for the type of infrared detector array that is used by NIRSpec. In addition to JWST, many ground based observatories use H2RGs today.
ISIM	The **integrated science instruments** module houses (and includes) JWST's science instruments.
ROIC	A **readout integrated circuit** (ROIC) is bonded to the HgCdTe detector array. The ROIC senses charge in the detector array and converts it to electrical voltages. The ROIC also multiplexes the array so that many pixels can be readout using only 4 amplifiers.
SCA	A NIRSpec **sensor chip assembly** (SCA) consists of an HgCdTe detector array bonded to a silicon readout integrated circuit and mounted on a molybdenum package. The SCA includes simple resistors and capacitors to filter electrical signals.

References

1. Rauscher, B.J. *et al.* 2007, PASP, 119, 768