

Simulating Satellite Streaks: LSSTCam Sensor Impact and Correction

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SLAC/Rubin Obs LSST Camera

With thanks to: Aaron Roodman, Adam Snyder, Homer Neal,
Dan Polin, Tony Tyson

Studying satellite streak impact on Rubin Observatory LSST CCDS

Satellite streaks challenge stringent [survey science requirements](#) on several fronts:

- Photometry: Billions of stars and galaxies to 27th magnitude, ~24th mag in each exposure with <5 millimag rms
- Shear: 3×10^{-7} statistical precision in object ellipticity across several degrees
- Time: 10 million alerts per night, unexplored faint transient sky on scale of minutes to years

Current LEOsats are brighter than 8th magnitude.

Masking their pixels, removing scattered light, and/or instrument signature removal all create **systematics**

Our goal: ensure these new systematics do not exceed the unprecedented statistical precision of the LSST



UC Davis Beam Simulator

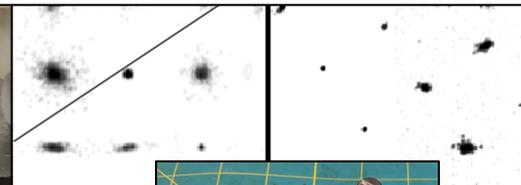
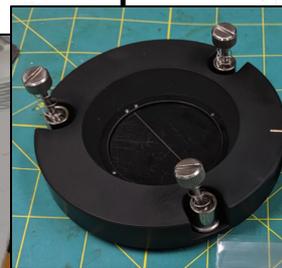
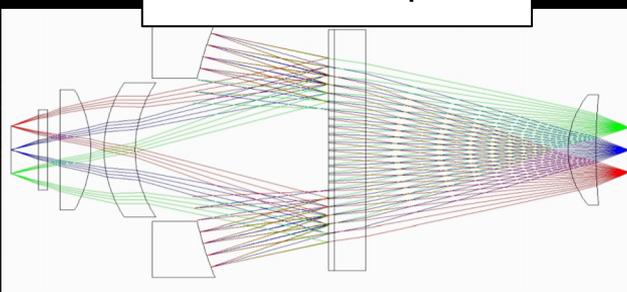
custom readout electronics

LSST e2v & ITL CCDs (both flavors available)

precision XYZ stage

LSST f/1.2 optics

scattering sphere and input mask with stars, galaxies, & sat streaks



Rapid CCD characterization under realistic conditions

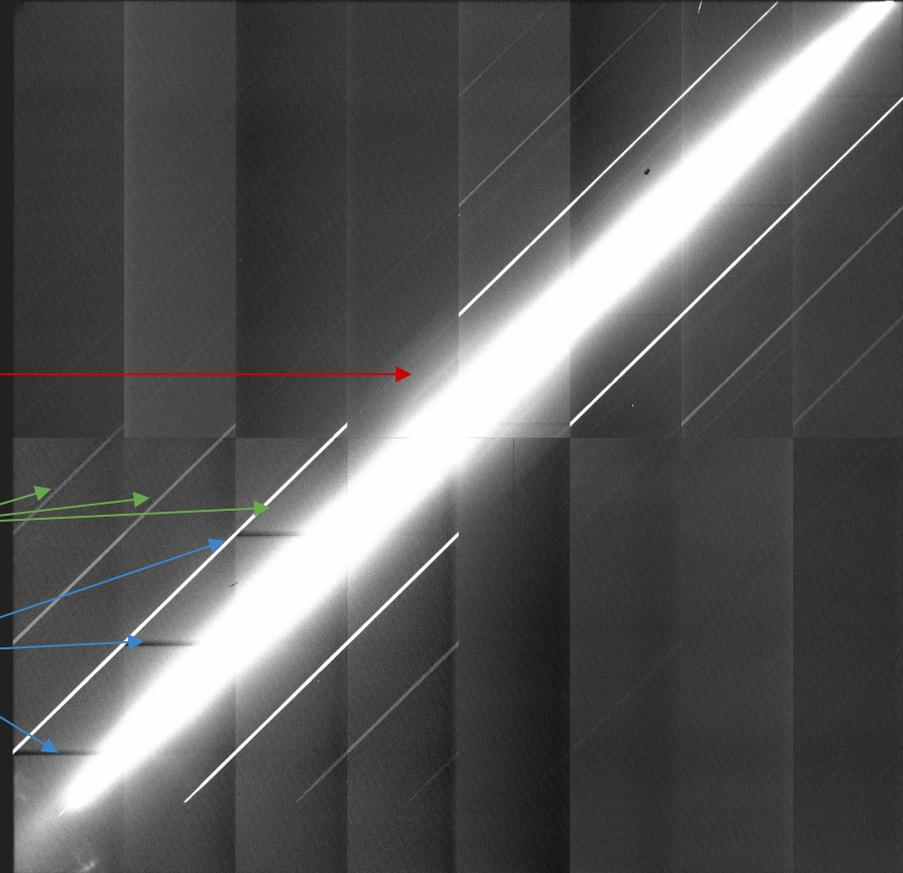
Simulating Satellite Streaks

Studies on LSST sensors began in July 2019 using LSST f/1.2 beam simulator, and studies with a spare raft are ongoing & full focal plane simulations planned. Several terabytes of CCD images of streaks under differing flux, position, orientation, voltage, and clocking

General observed behavior in simulation:

- **Scattered light** extends trail across segments
 - Main trail extends above read noise for hundreds of pixels, sky level for a few dozen
- Multiple orders of **crosstalk** between segments
 - +/- 1E-4 to 1E-6 in amplitude
 - Non-linearity of crosstalk vs. signal
- **Bias shift** at some CCD segment crossings
 - Fixed in firmware update

Tallest pole after main streak removal is **crosstalk, which multiplies main streak across affected CCDs. Non-linear correction algorithm under development**



Crosstalk vs. satellite streak peak shows non-linear behavior

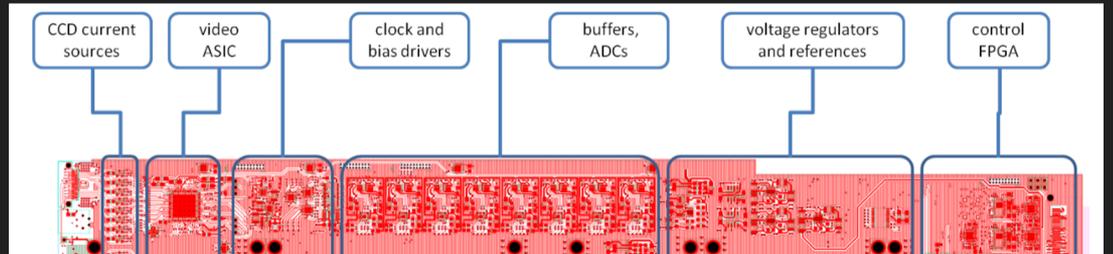
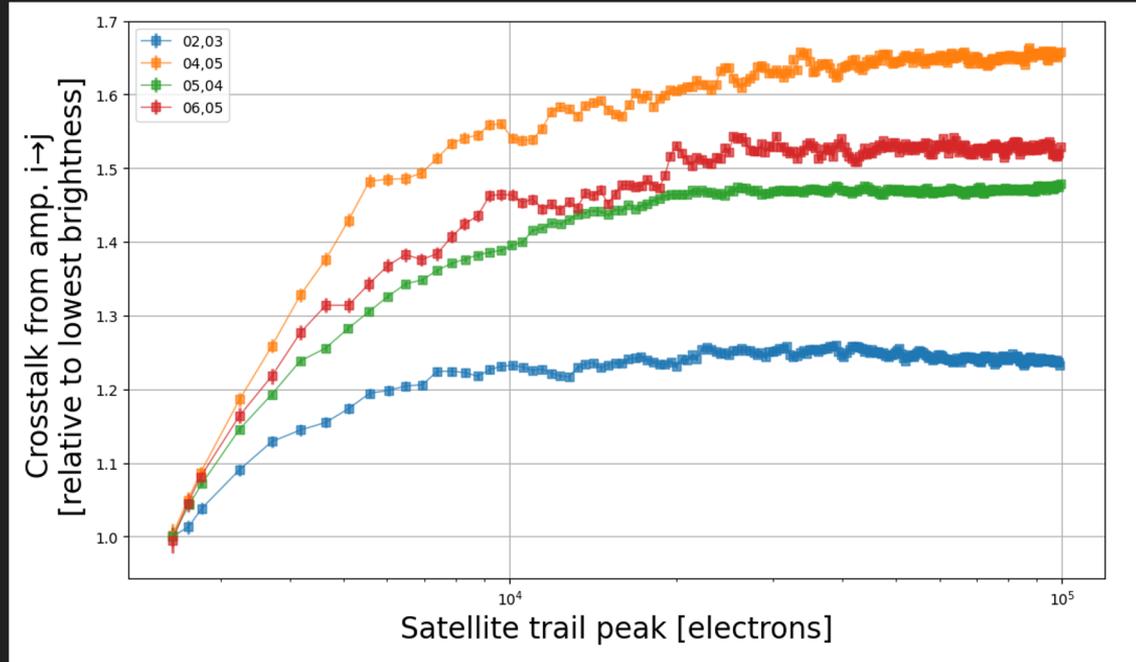
Bright satellites leave disproportionate amount of crosstalk in nearest channels

Possible sources:

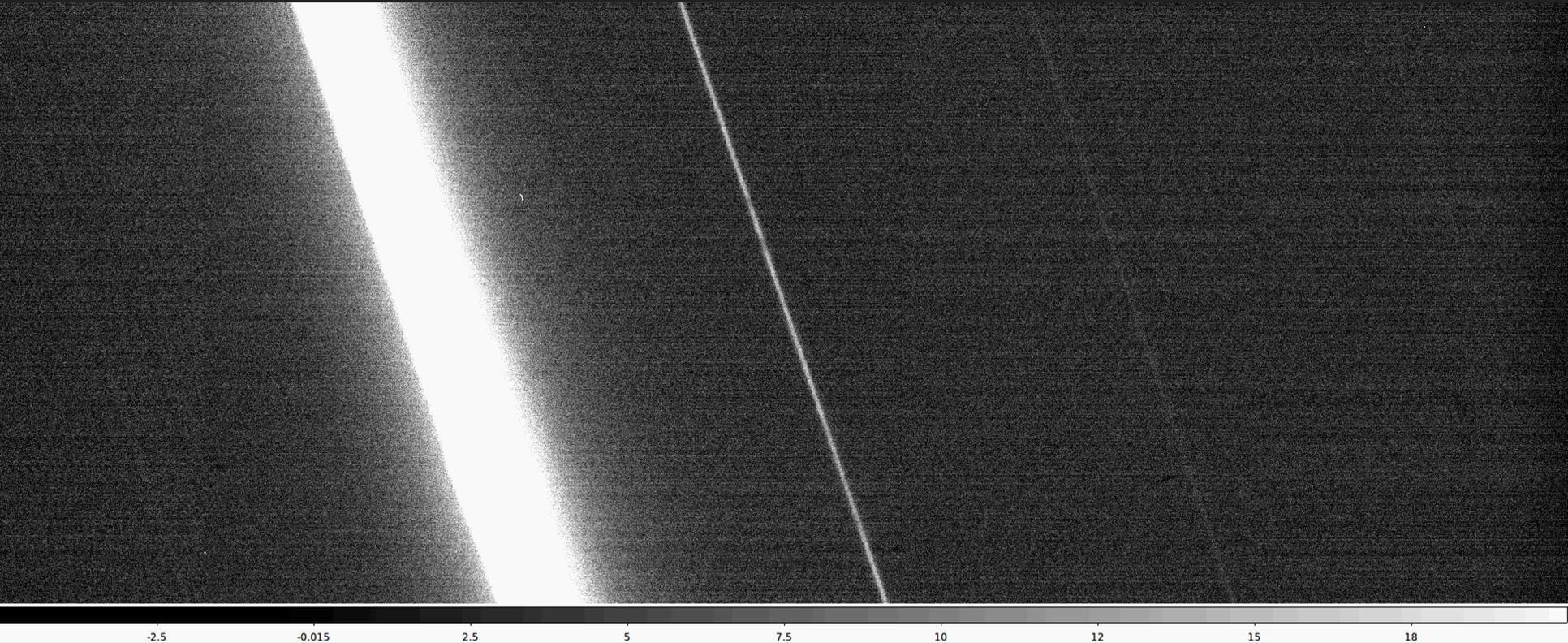
- On-chip, during CDS
- Flex cable from CCD to electronics (+/- preamp)
- Pixel processing chips
- Coupled reference voltages
- Anywhere channels meet... cables, metallic traces, etc

Caveat: UCD pixel processing differs (only same CCDs & connector) but both show non-linear behavior

LSST readout electronics board →
Each board carries 3 CCDs w/
independent readout electronics

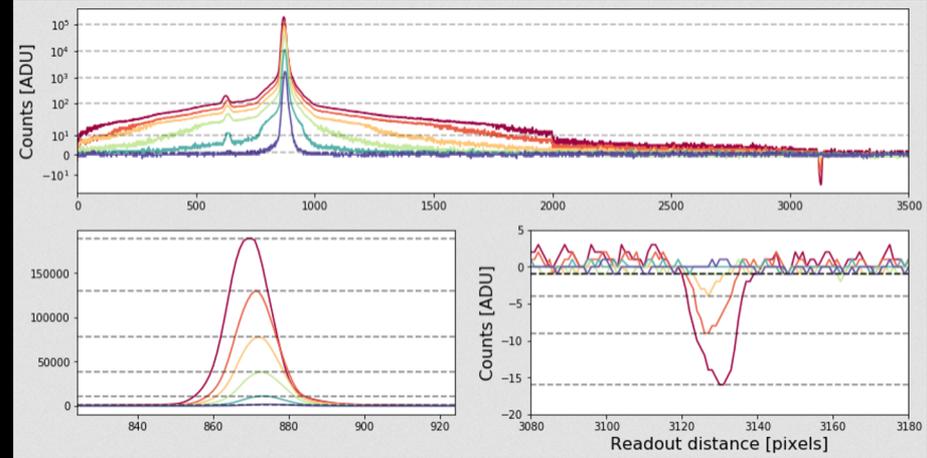
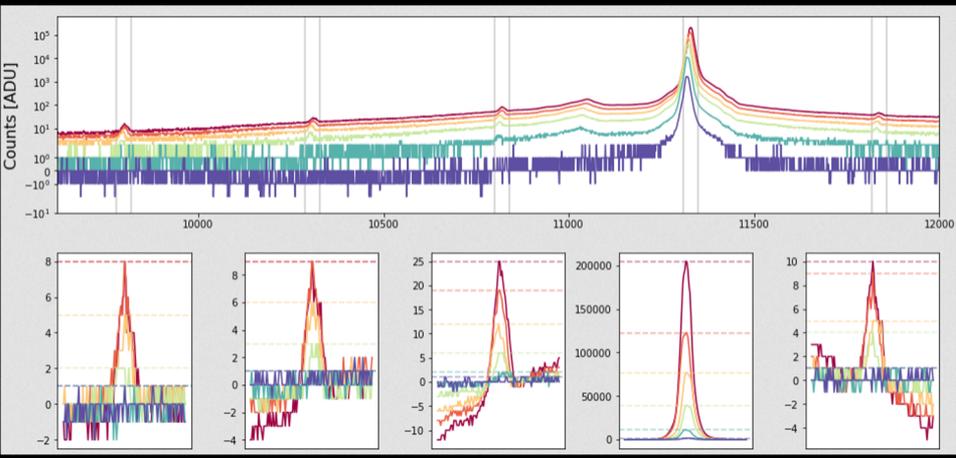
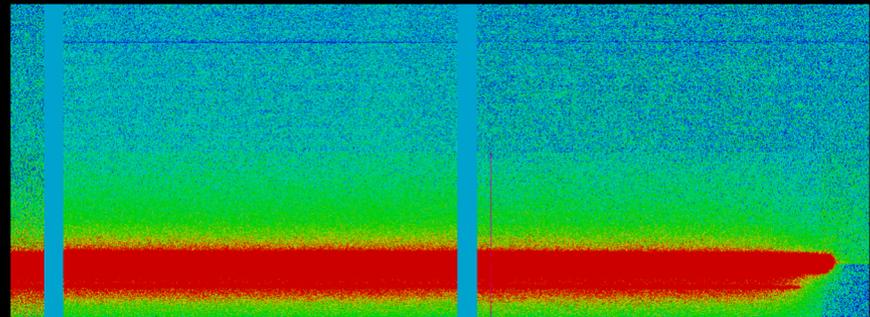
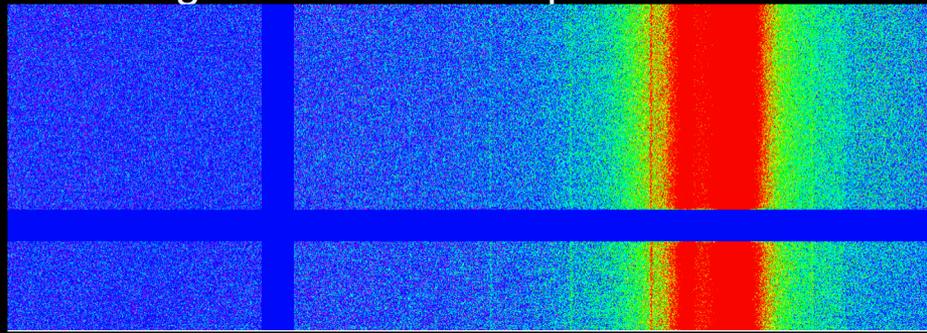


Beam sim satellite streak and crosstalk correction



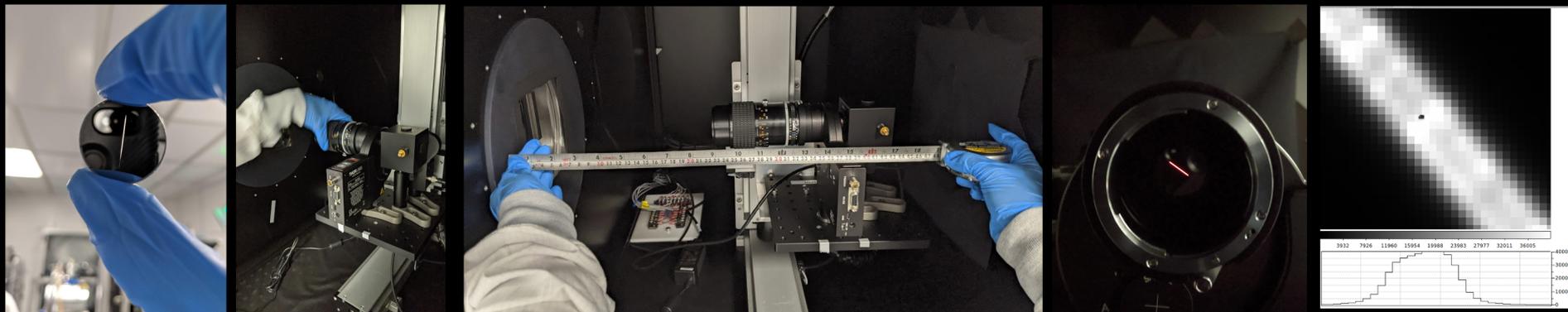
10-20k e⁻ peak (~Darksat) corrected with non-linear matrix method

First streak simulation at SLAC with spare raft & LSST electronics: Scanning focused laser in parallel and serial directions → broad streak but crosstalk revealed

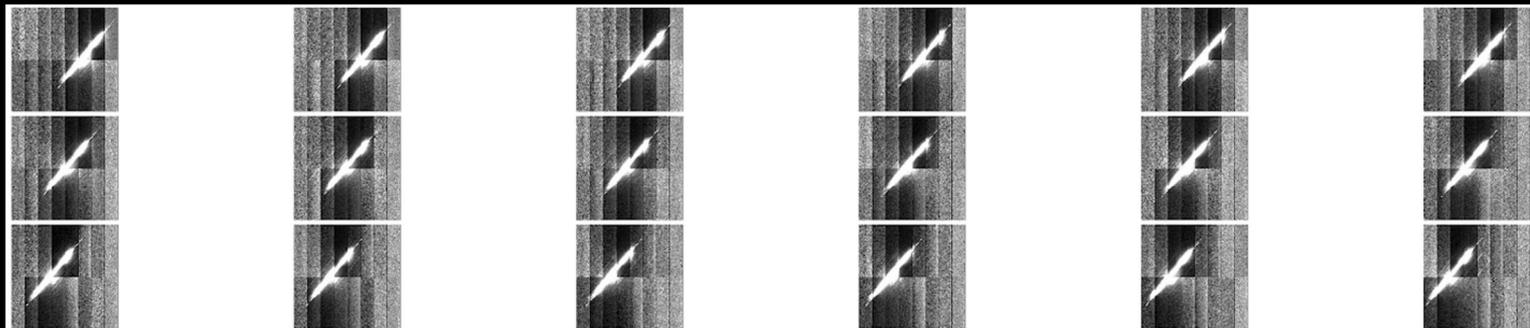


Positive crosstalk in serially-adjacent channels, negative crosstalk across mid-line channels
Bottom line: with crosstalk no greater than a part in ten thousand, satellites below $\sim 10k e^-$ leave
crosstalk streak in read noise

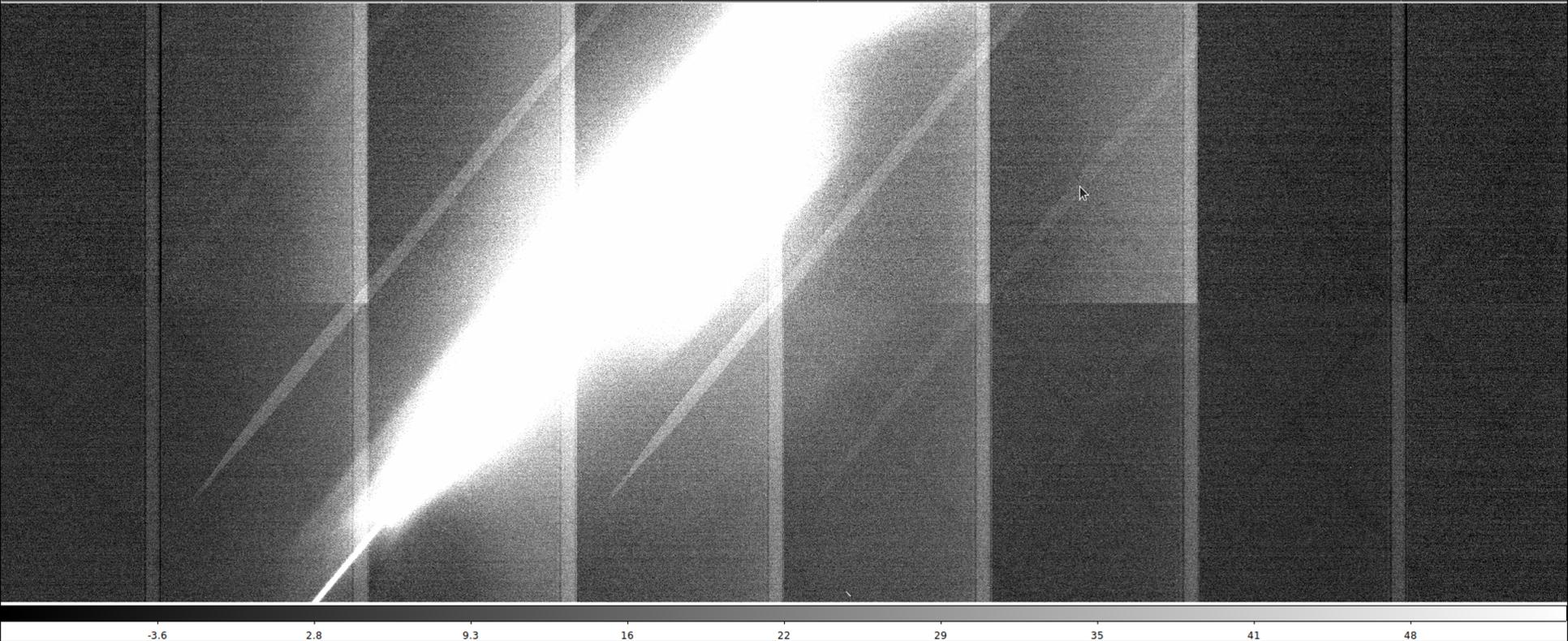
Second streak simulation at SLAC with spare sensors: 10 μm wide photolithographic slit \rightarrow 10 pix FWHM w/ spot projector lens LSST electronics & config, but optical beam not f/1.2



Slit mask, projector & test stand dark box, down the barrel with the red laser on, & streak images

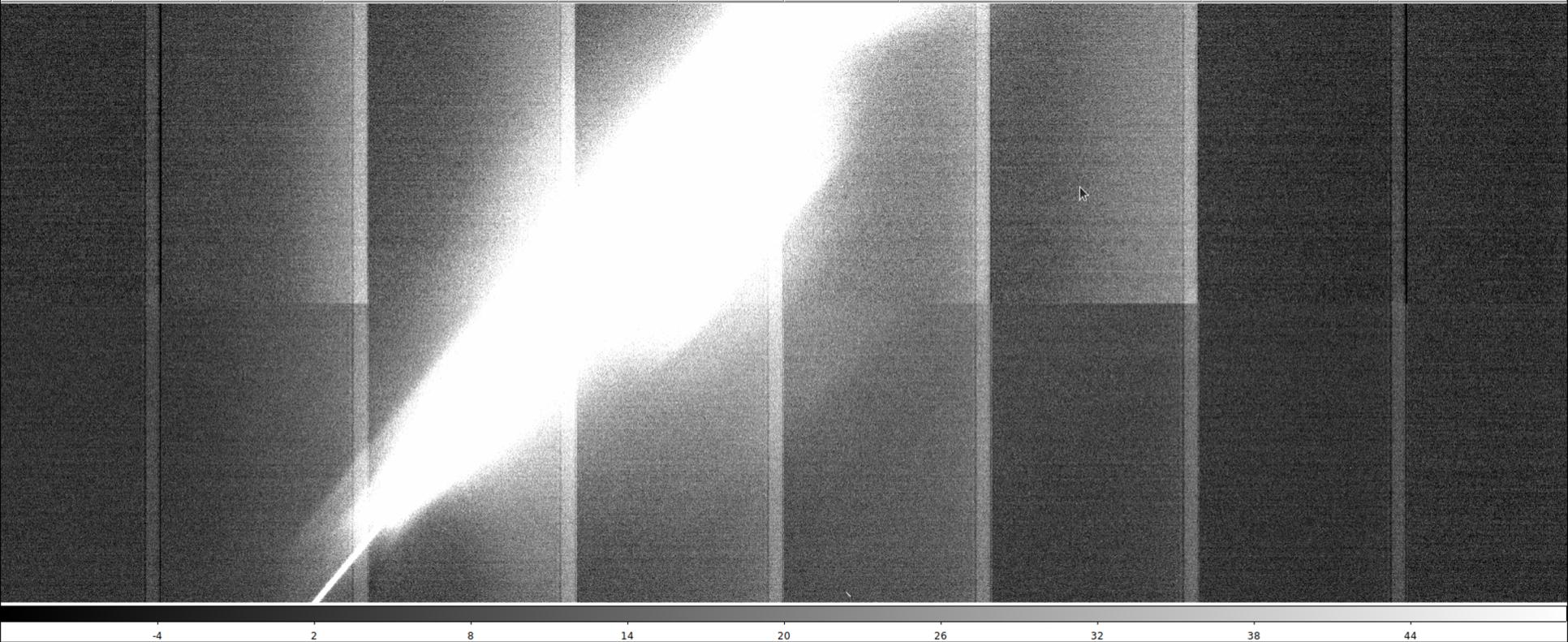


Problem: Sat streaks multiply into a linearly-correlated mess LSST CCDs + electronics under nominal operation



Bright streaks produce visible levels of positive and negative crosstalk in nearby segments
Orthogonal directions from 2nd CCD flavor (ITL) having opposite readout directions top-bottom

Solution: Correct crosstalk w/ non-linear matrix coefficients



Smallest coefficients and those which are affected by scattered light have largest residuals. ¹⁰
Residuals needs coadd science analysis to infer impact on e.g. cosmology or NEO discovery.

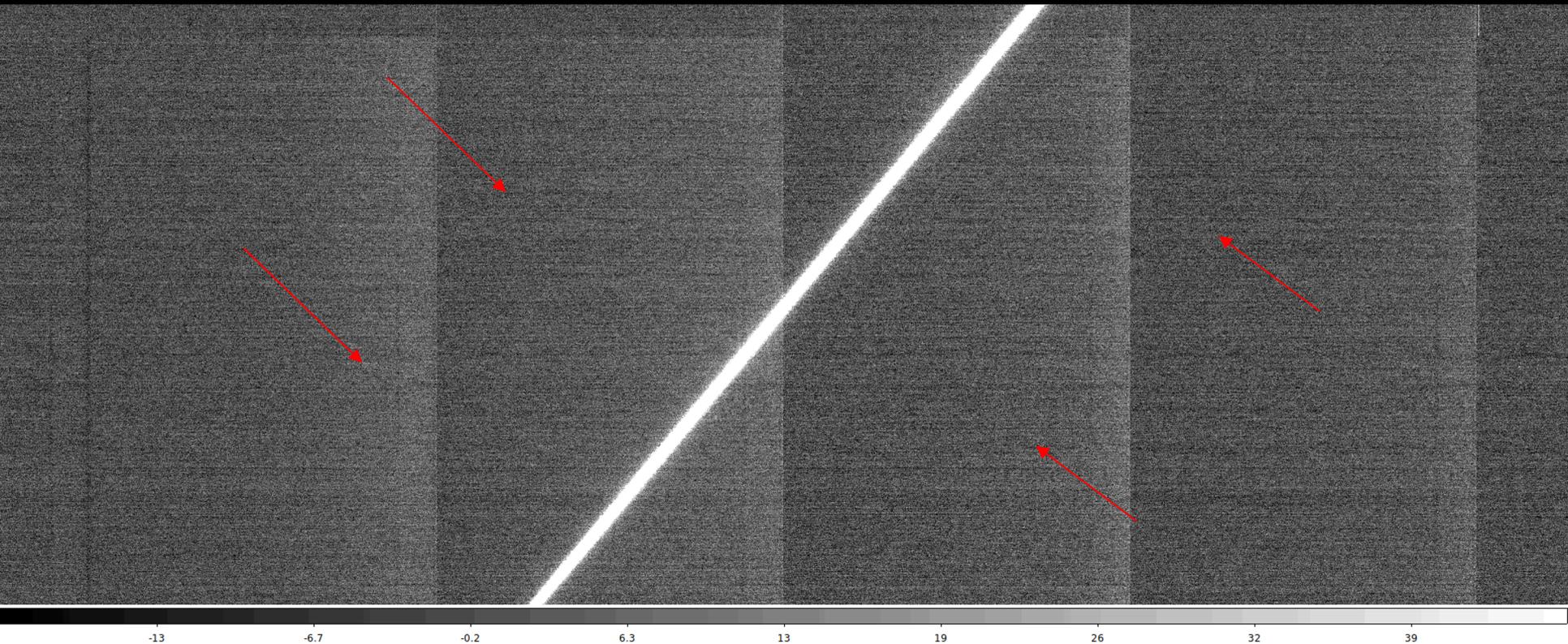
Raw crosstalk vs. brightness images on spare ITL raft

1k-200k electron peak \rightarrow \sim 0-50 electron xtalk pattern



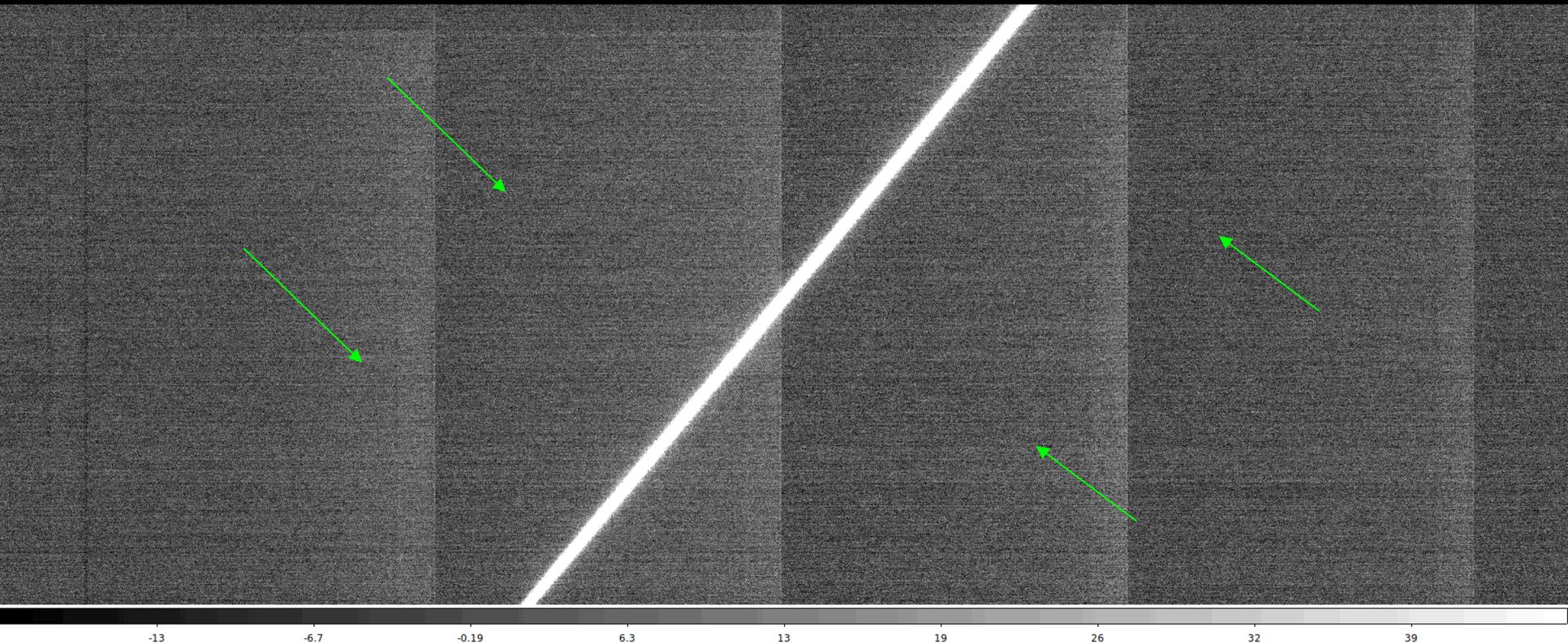
ITL crosstalk vs intensity - corrected w/ linear matrix

~10 electron residuals when using xtalk matrix measured from saturated source



ITL crosstalk vs intensity - corrected w/ non-linear matrix

No visible residuals. Next: measure performance metric on coadd & dithers



Physical crosstalk mitigation studies:

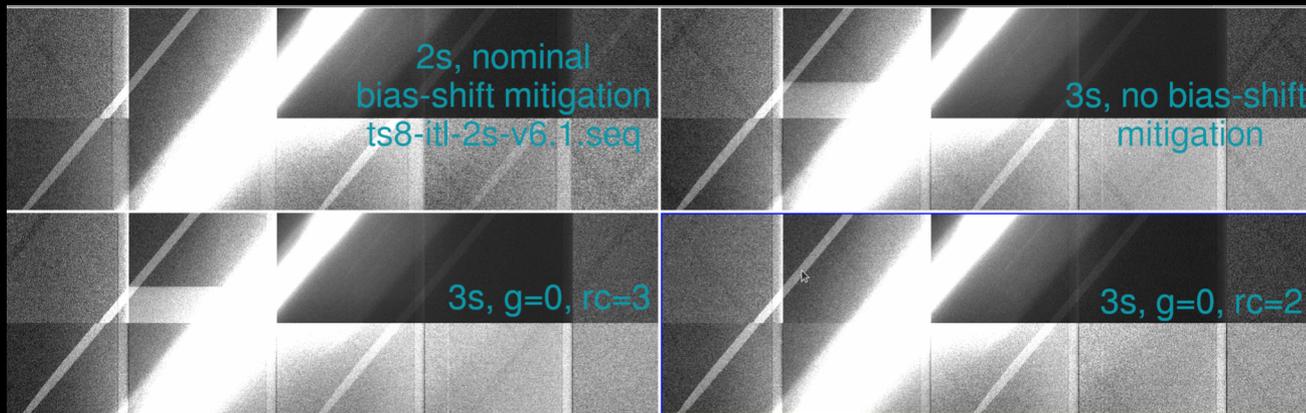
Determine origin through bench-top measures and readout optimization

Pixel processing chip (ASPIC)

Gain and RC constant in chip → different crosstalk pattern

Reading out slower (2s → 3s) also reduces crosstalk, but comes at survey efficiency cost

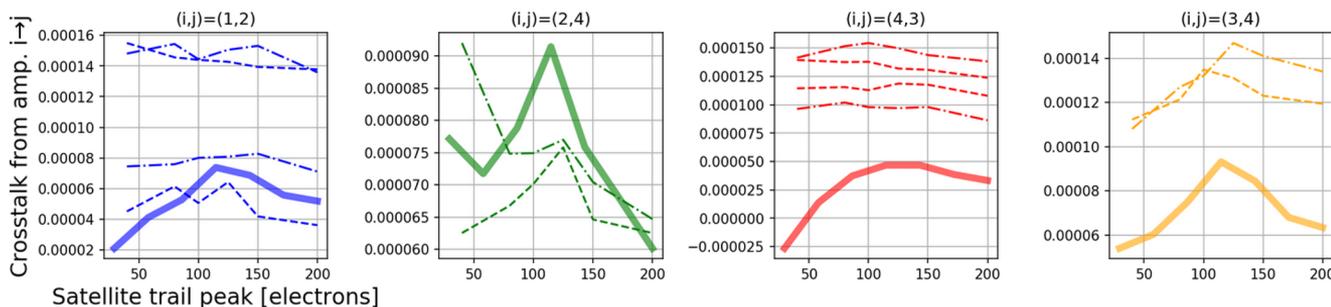
However (ASPIC) can't explain all **Crosstalk vs. flux non-linearity**



Bench-top measure of ASPIC*

from signal injection (thick line) compared to images (dashed) showing 4 channel pairs (colors)

Multiple sources of crosstalk to disentangle

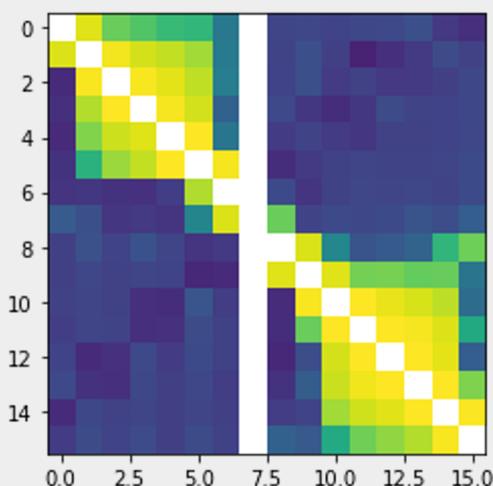


Comparison of the LSST crosstalk matrix via differing methods

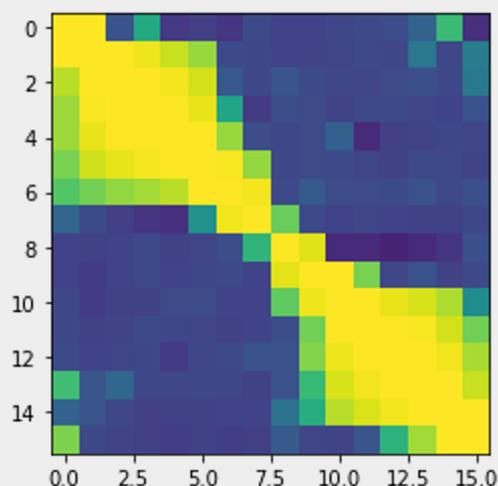
Planned on-sky measurement of crosstalk via stars

Satellite streaks can provide similar calibration

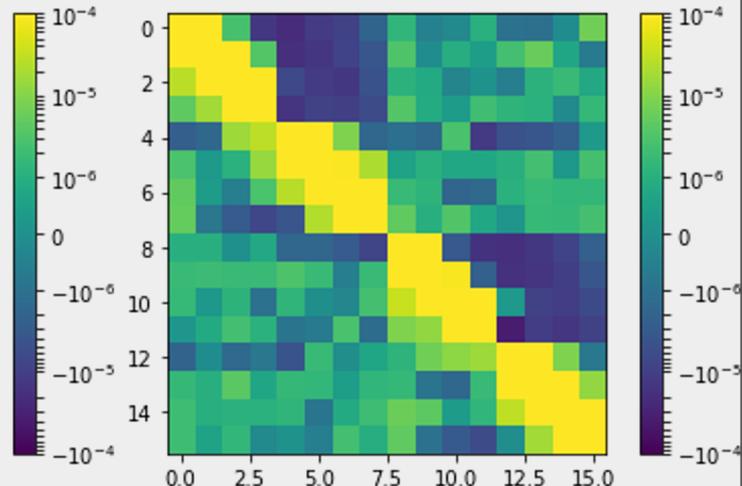
ITL xtalk via streaks



ITL xtalk via stars



e2v xtalk via stars



Crosstalk amplitude depends on proximity of other channels and flux
Typically $+1E-4$ on nearest neighbors, $\pm 1E-6$ on furthest channels

Conclusions and Next Steps

Streak simulations performed under varying conditions. Methods used:

- Re-imaging adjustable-width mask using LSST beam simulator @ Davis
- Focused laser spot + dithering across raft, re-imaging photolithographic slit @ SLAC
- Other options: laser line generator (laser + cylindrical lens), pinhole camera reimaging scene

Satellites cause long streaks of correlated noise & signal which is multiplied via crosstalk

- Crosstalk is among 1st steps of ISR, needs to correct far better than 1% → 1 part in 1E-6
- Non-linear crosstalk correction unexpected and worrying, but method appears to be working
 - Requires some more thoughts about measurement & implementation
 - Requires science validation that residuals are acceptable
- Reducing satellite streak crosstalk via operation and readout feasible, work underway

Ultimately, darker = better.

but, dimming to ~8th magnitude puts crosstalk into the read noise

Next: can we model and remove the main streak, or must we mask?