Propagating Per-Pixel CMOS Noise in Data Pipelines and Ideas for Future Modeling

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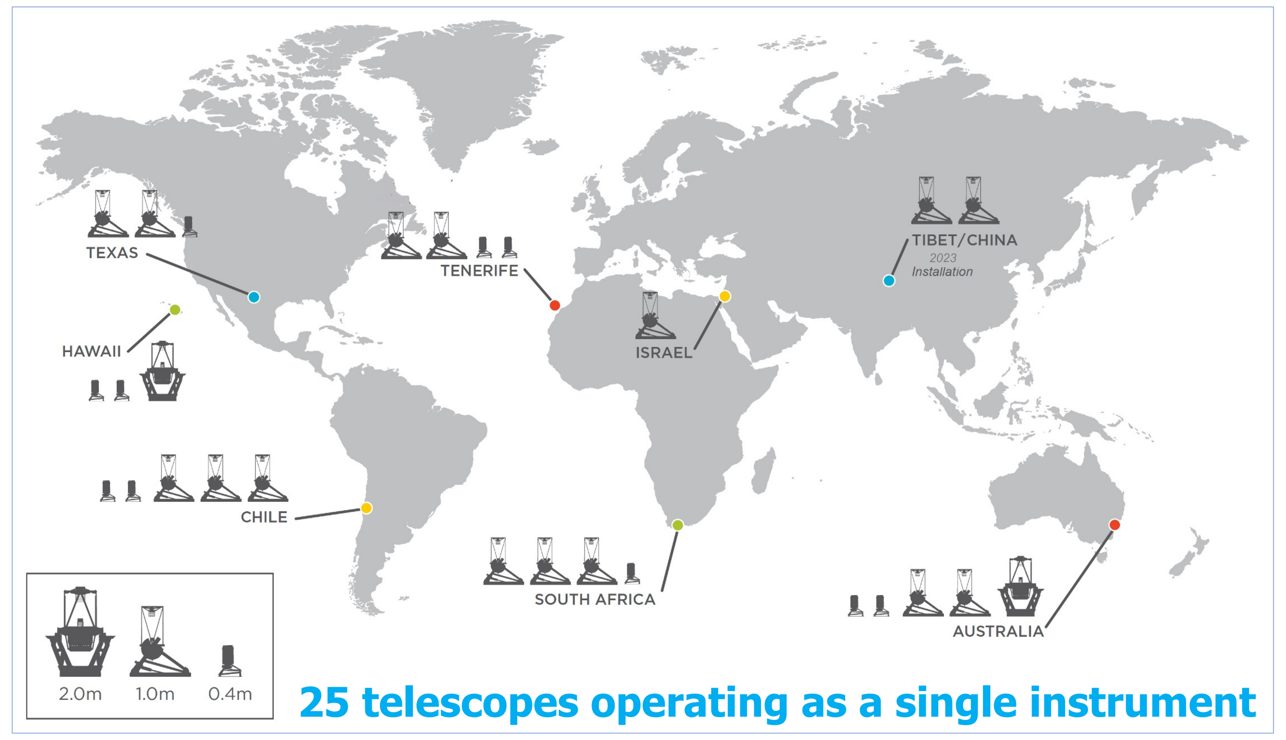
Las Cumbres Observatory

- A global network of >25 telescopes.
- Imaging & spectroscopy on 2,1,and 0.4 meter apertures.
- Automatically scheduled, fully robotic operations.
- Longitudinal & latitudinal coverage to facilitate 24/7 time domain astronomy.
- Introduced QHY600 CMOS cameras 2023 in the 0.4m education network (10 telescopes).

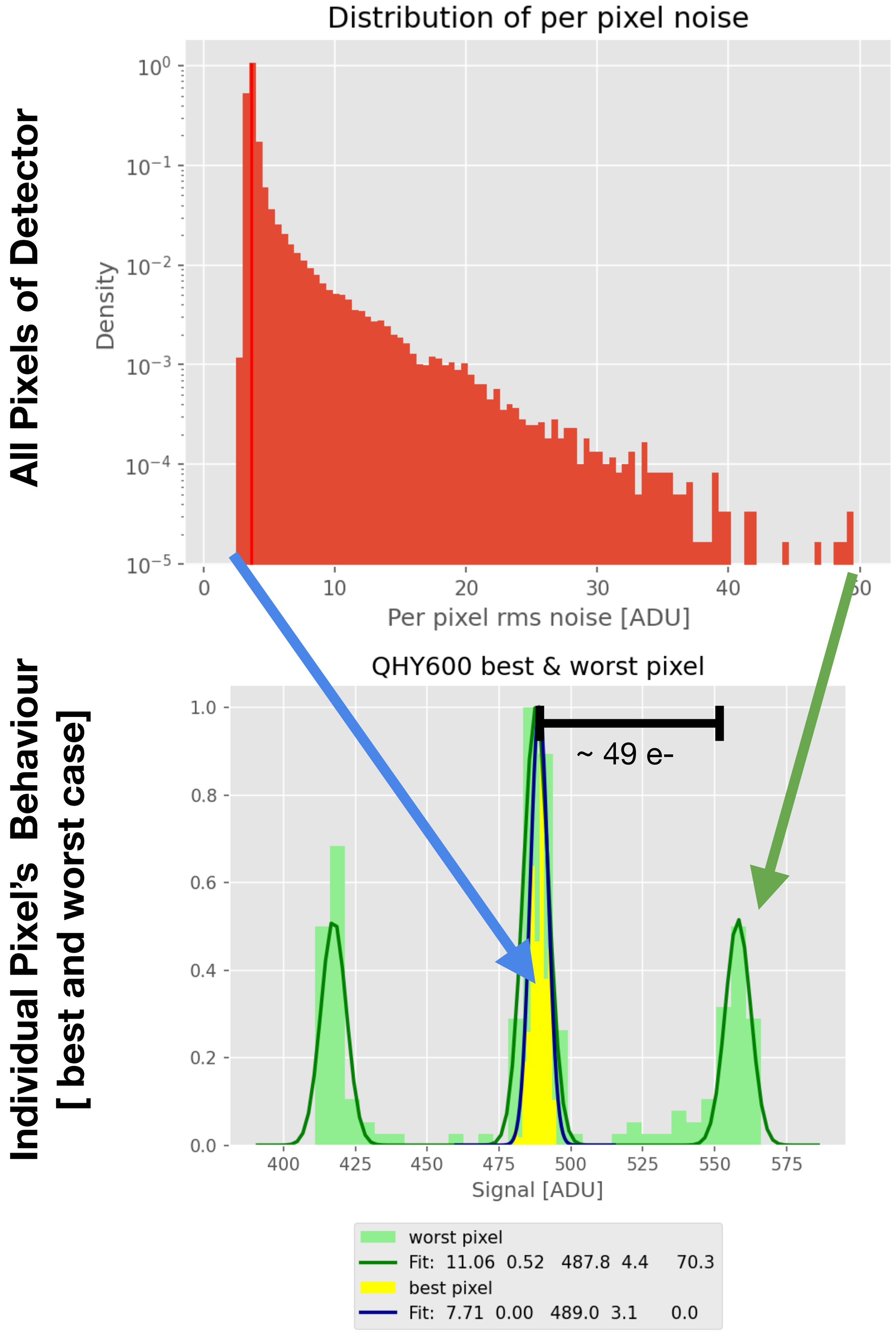


Noise in CMOS Sensors

- Each pixel has an individual amplifier circuit:
  - A single read noise value is insufficient to characterize entire detector as in a CCD.
  - **Readnoise is a now a quality of individual pixels**.
- Additional noise: Random Telegraph Noise (**RTN**).
  - Caused by lattice defects in MOS amplifier circuits, operating at very low current.
  - Correlated double-sampling can lead to 3 responses for a given input level (or 2, or more).
  - Different pixel responses can be several 10s of electrons apart. About 5-10 % of pixel affected to some degree.

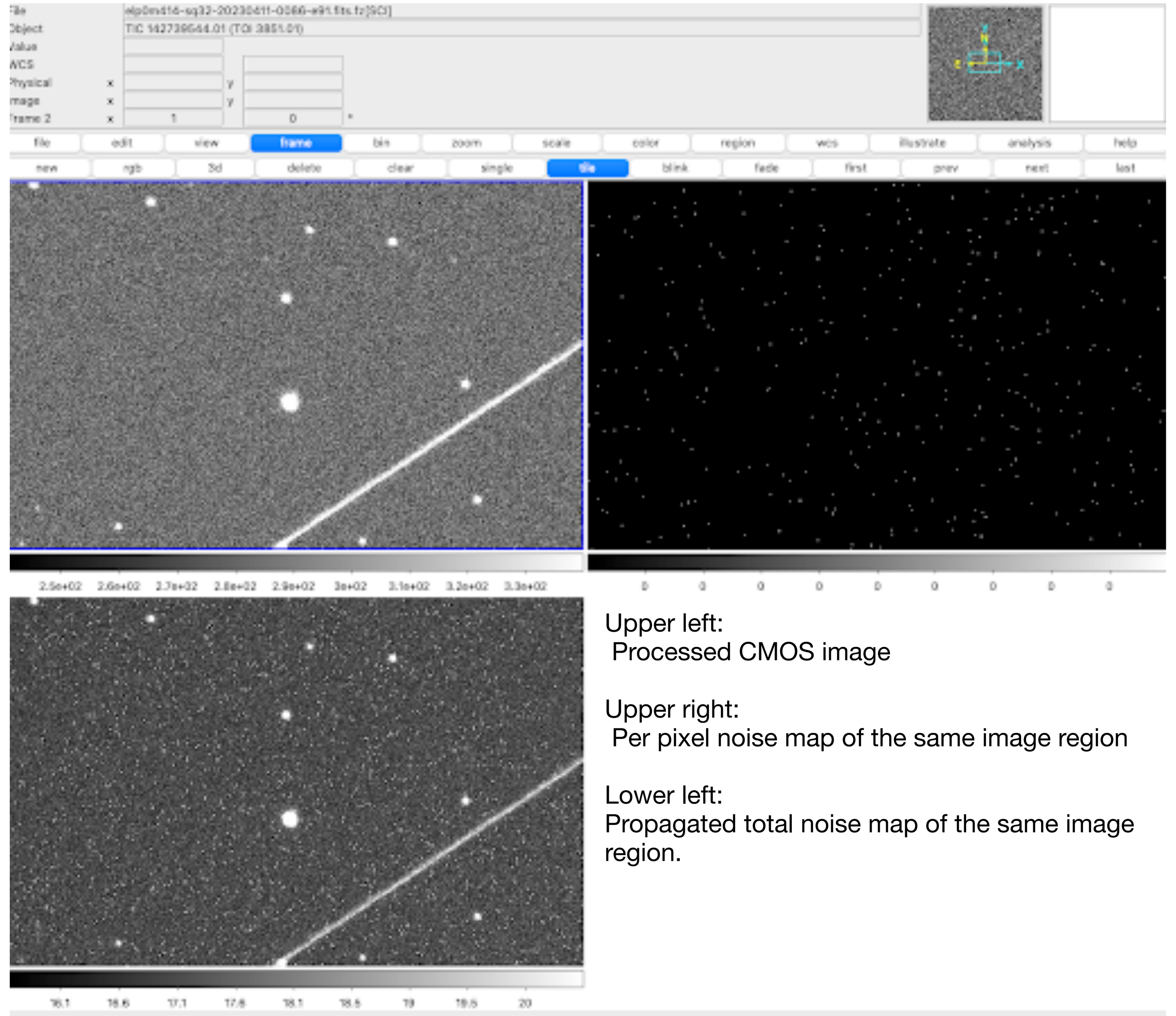
Modelling CMOS Noise

- **Simple:** Measure noise in a series of bias images.
  - Simplify as Gaussian process. Derive a CMOS Noise Map.
- **More advanced**:
  - Model with 1 to 3 gaussians: derive peak separation.
  - Machine learning approach: Gaussian Mixture Modeling.
    - Leverage machine learning algorithms & libraries.
    - Future execution on GPUs?
- Complete modeling very computing-intensive:
  - QHY600 (9k x 6k pixels) takes several days to compute.
- See https://cmos-noise-map.readthedocs.io/ for more.



Propagating per Pixel Noise

- At Las Cumbres Observatory, all data processed with BANZAI data pipeline.
  - Overscan, bias, dark, flat correction -> extract source catalog -> fit WCS solution.
- Noise propagation build into BANZAI pipeline.
  - Seeded with CCD single read noise, propagates read and shot noise throughout calibration products to final image.
  - **Noise propagation for CMOS imagers is seeded with a per-pixel noise map.**
  - BANZAI catalog extraction uses the per pixel noise map for CMOS imagers.
  - User decides to utilize noise map or not.
- Gaussian pixel noise model practical but incomplete for RTN.
  - Full propagation of RTN parameters per pixel?
  - At this time, no known photometry code to handle RTN.



Upper left: Processed CMOS image

Upper right: Per pixel noise map of the same image region

Lower left: Propagated total noise map of the same image region.

Compensating RTN Noise

- RTN not relevant for high S/N cases, but for low signal situations:
  - Bias, dark calibration products.
  - Low sky level, low exposure levels, e.g., UV satellites.
- Mitigation: Use RTN distribution as a prior.
- Example of stacking bias images (here: a single pixel).
- Investigate convergence using first N images:
  - Simple mean vs full RTN modeling + maximum likelihood fitting.

With modeling of Random Telegraph Noise, bias stacking converges fast. Bad RTN pixels can be useful!

- Computationally very expensive, estimate ~ 3-4 hours per full-frame bias stack of 9kx6k pixel image on CPU.
- Good candidate for future GPU implementation.
- Potential for future integration in pipelines (bias, dark).
- Rethink photometry code?