Photon Counting Arrays for Dim Beacon Tracking in the Near-Infrared

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April-2016

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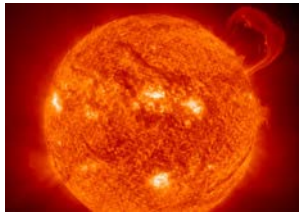
Deep Space Optical Comm Scenario



Sun
Can be field of view
Primary source of optical noise

Deep Space Optical Transceiver
Large distance
Large $1/R^2$ range loss
Large 2R/c round-trip light time (RTLT)

Point-Ahead Angle

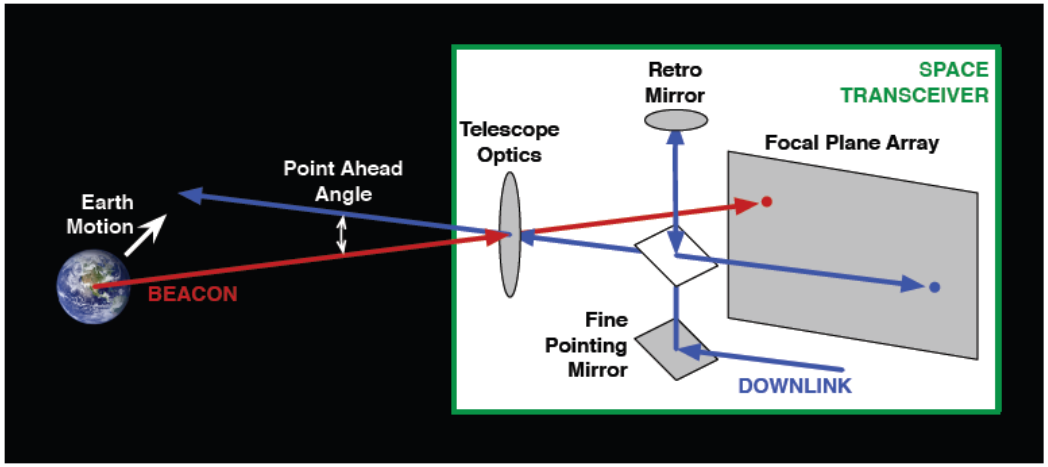
Downlink
- Stabilized by vibration isolation system & uplink beacon
- Gb/s return link data
- Ranging

Earth at T_1+RTLT

Earth at T_1

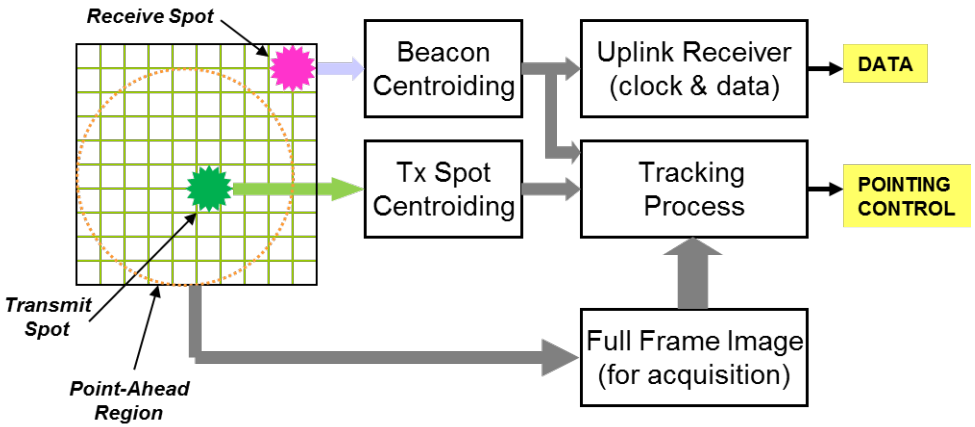
Uplink ("Dim Beacon")
- Blind points to spacecraft
- Aids downlink pointing
  - *Reference for removal of S/C jitter*
  - *Reference for point-ahead angle*
- Mb/s forward link data
- Ranging

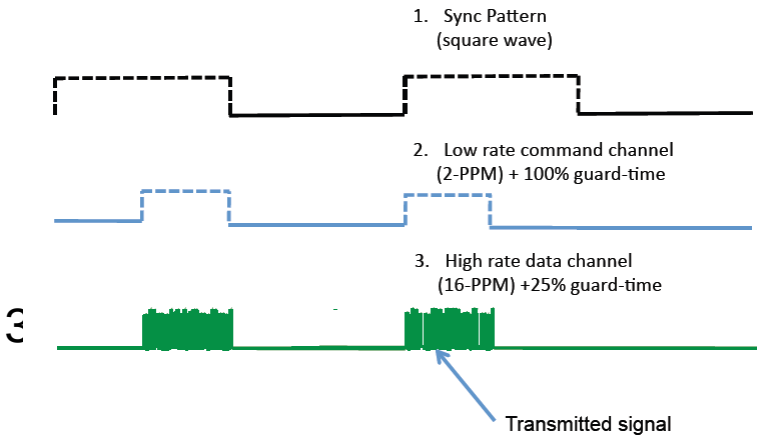
- **Uplink receiver assembly:**
  - Must form an accurate estimate of the location of the dim laser beacon to point the transmit beam to the Earth receiver location
  - Must track the angle of the transmit beam to confirm the point-ahead angle
  - Utilizes a nested beacon modulation scheme to support background subtraction and multi-rate uplink data



Acquisition, Tracking, and Data Detector

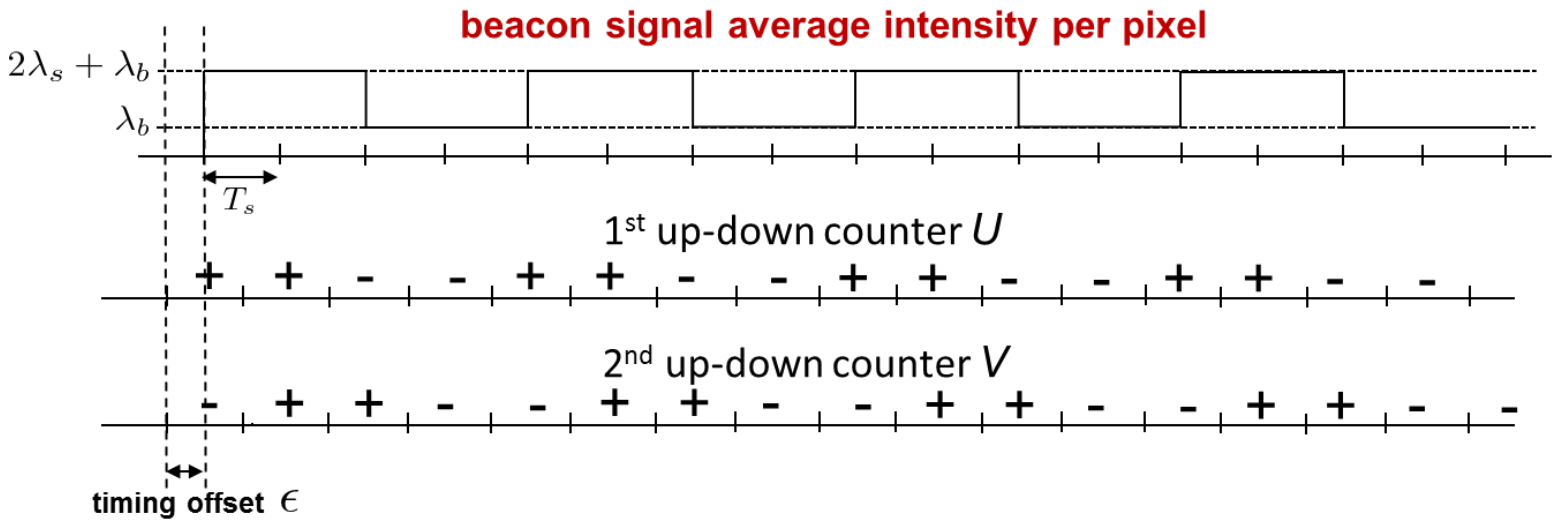
- **Single focal plane receiver architecture for simultaneous acquisition, tracking and uplink data demodulation**
  - Versus two or three typical for an optical receiver design
  - Reduces transceiver mass – Increases transceiver reliability
- **Nested uplink modulation scheme comprised beacon sync, low rate data channel, and optional high rate data channel**
- **Square wave beacon enables background subtraction, improving statistics for signal detection and position estimation.**
  - Background subtraction is implemented using a pair of up-down counters offset by command channel slot width
  - 50% average duty cycle beacon is optimal for signal estimation





Up-down Counter Statistics

- **Up-down counters alternately increment and decrement pixel counts at beacon frequency**



- The up-down counter (UDC) outputs U and V have mean and variance

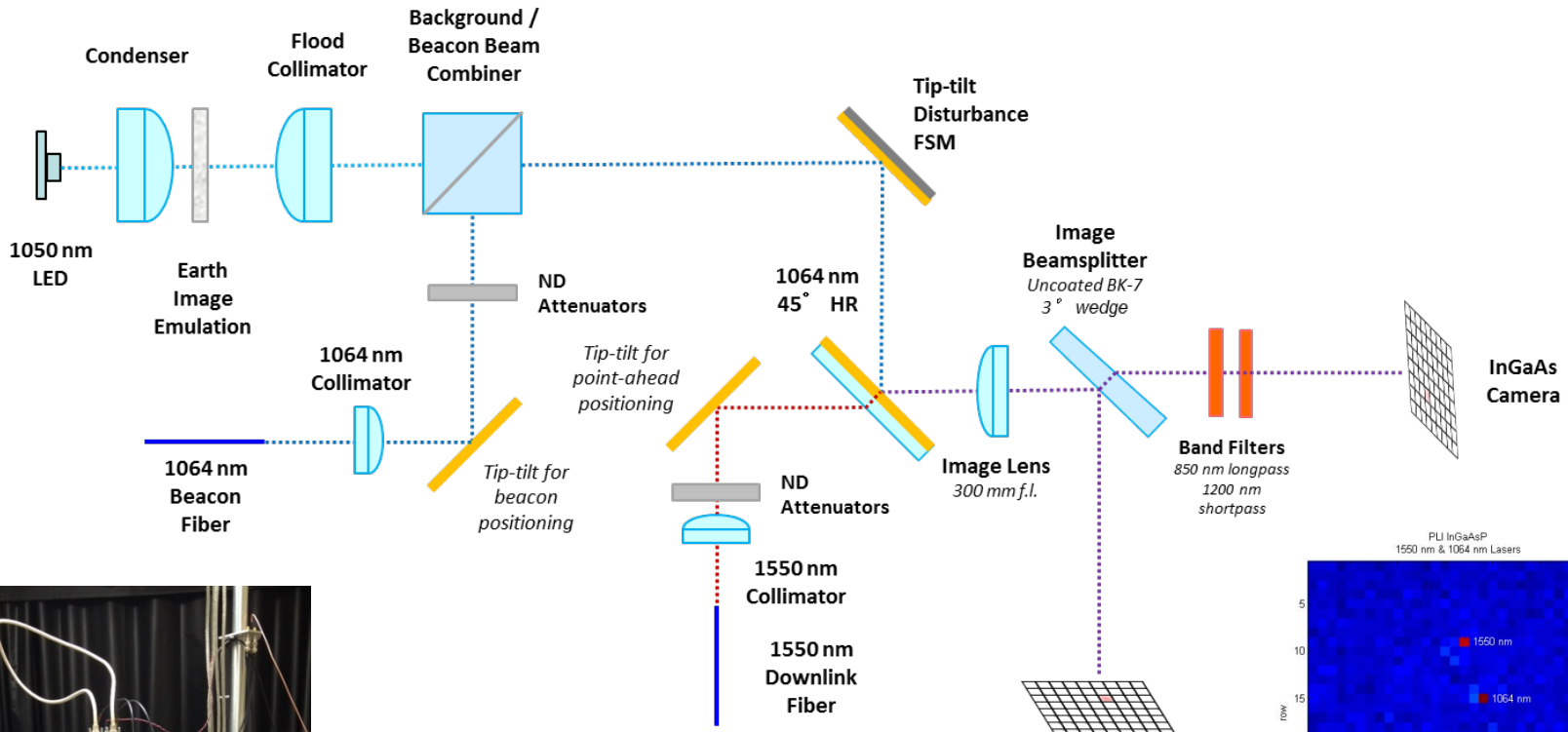
no dependence on background

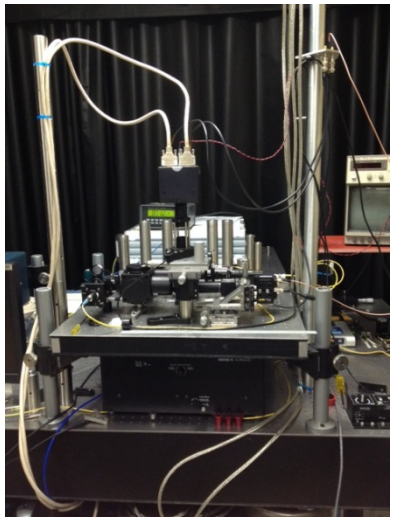
$$E[U] = 4N(1-\epsilon)\lambda_s T_s, \qquad Var[U] = 4N(\lambda_b + \lambda_s)T_s$$
$$E[V] = 4N\epsilon\lambda_s T_s, \qquad Var[V] = 4N(\lambda_b + \lambda_s)T_s$$

where N is the number of beacon cycles, ε is the slot timing offset, and T_s is the slot time.

- Use of square law statistic $W = U^2 + V^2$ allows centroid estimation without temporal synchronization.
- Modified square law statistic $W^* = U^2 + V^2 - 2S$, where S is up-counts, removes background dependence from mean of square law statistic W.

Photon Counting Camera Testbed Optics





PCC testbed optics mounted on vibration isolation stage. The vibration isolation stage can be tuned to break frequencies as low as 0.5 Hz in three axis to minimize impact of room vibrations on long integration centroiding measurements.

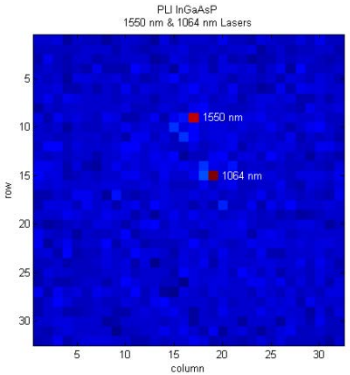
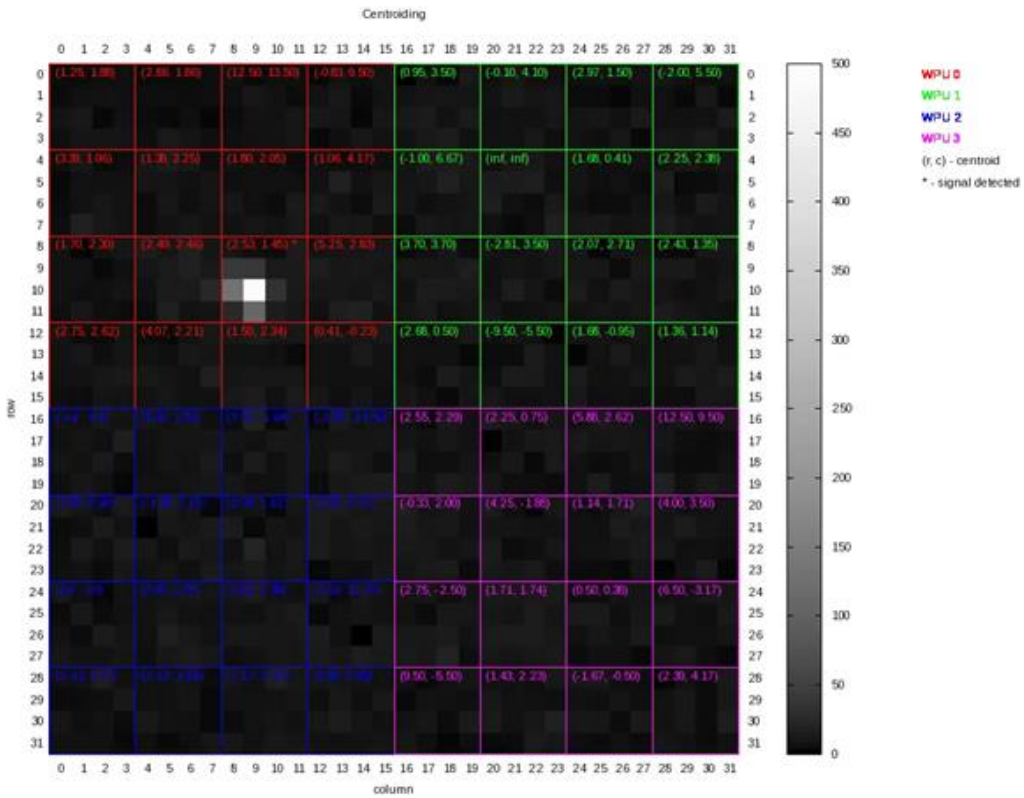
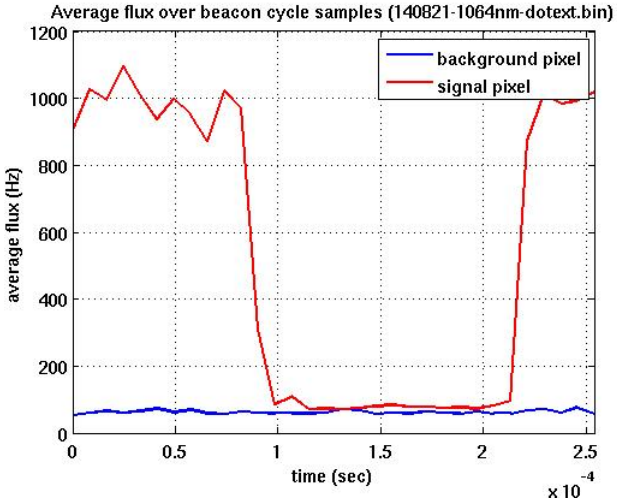


Image with 1064 nm beacon and 1550 nm downlink spots. Image is synthesized from photon arrival timestamps.

Modulated Beacon Acquisition

- **Acquisition with outer code modulation**

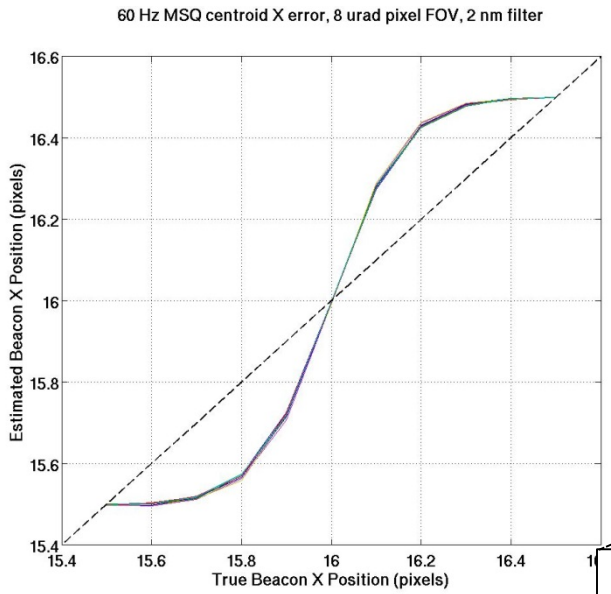




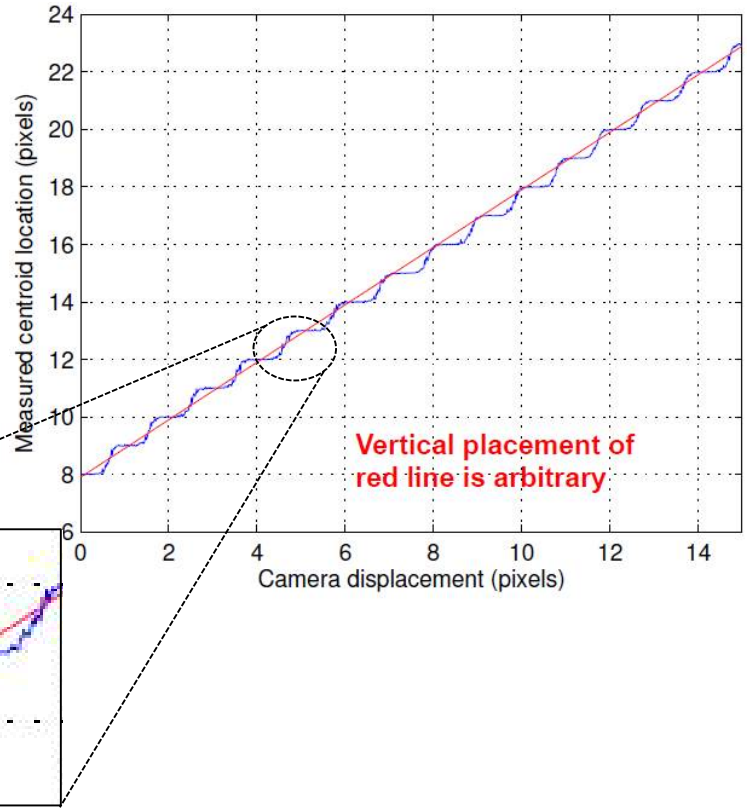
Centroid Characteristic

- **Centroid characteristic curve is dependent upon pixel size, beacon spot size, and signal and background flux rates**
  - Simulations and measured testbed centroid values show qualitative agreement

Simulated centroid characteristic curve

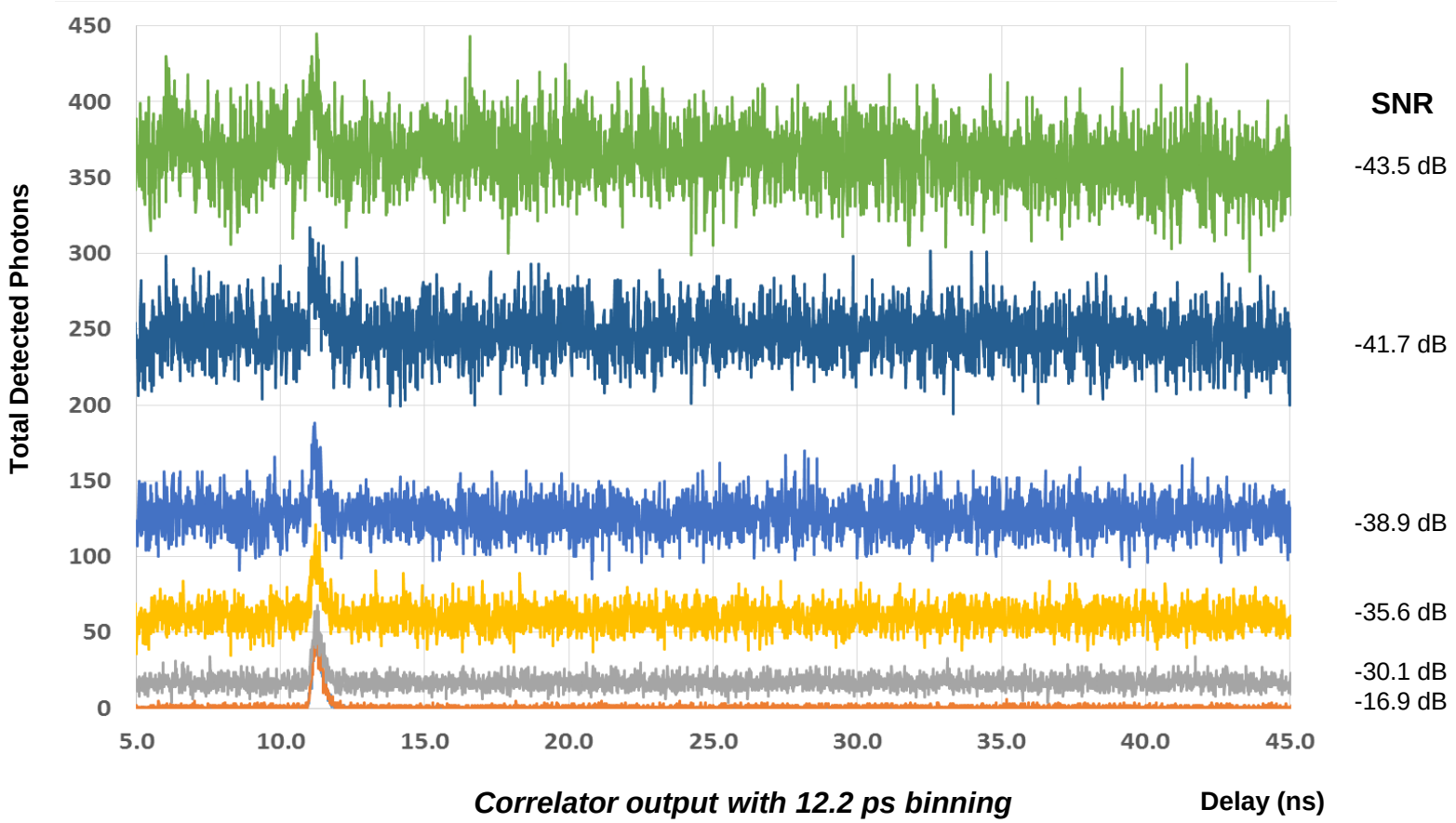


Measured centroid v. beacon displacement



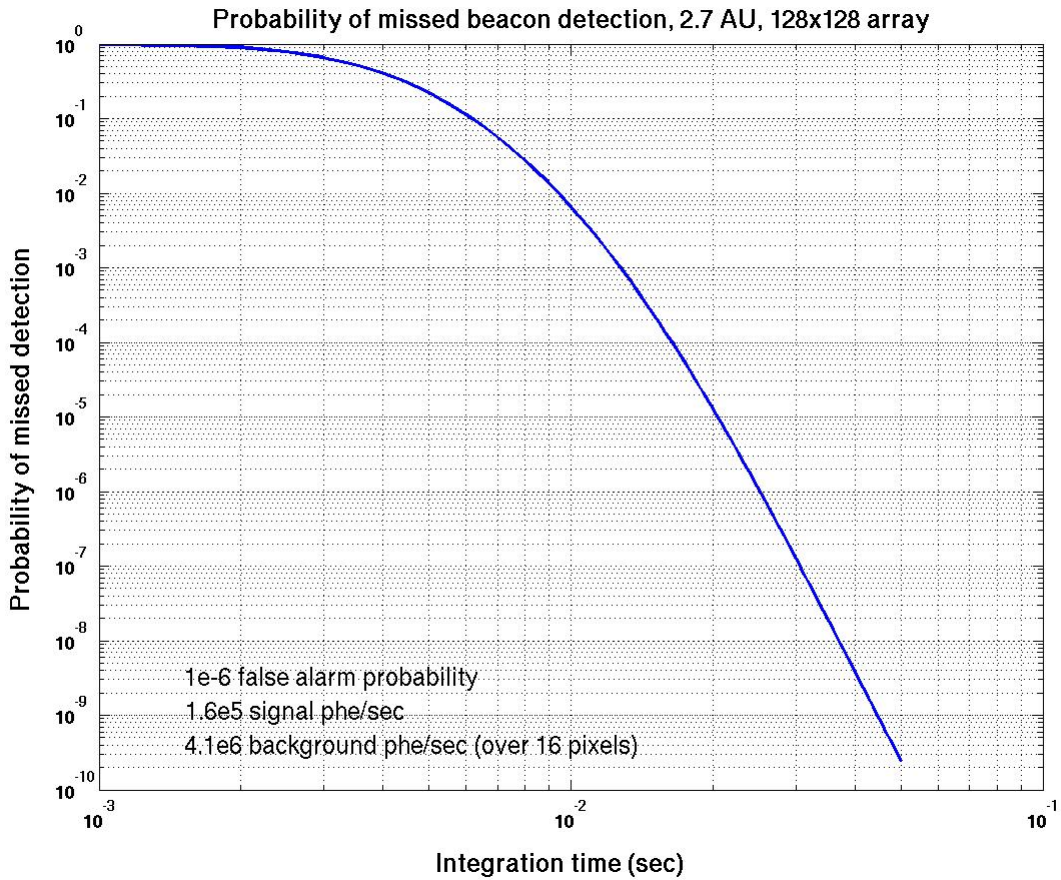
Negative SNR Acquisition Limits

- **Have performed separate experiments with single pixel, free-running detectors to demonstrate acquisition limits in highly negative (dB units) average signal power to average noise power regimes**
  - Below example for <100 ps pulse at 1 MHz repetition rate

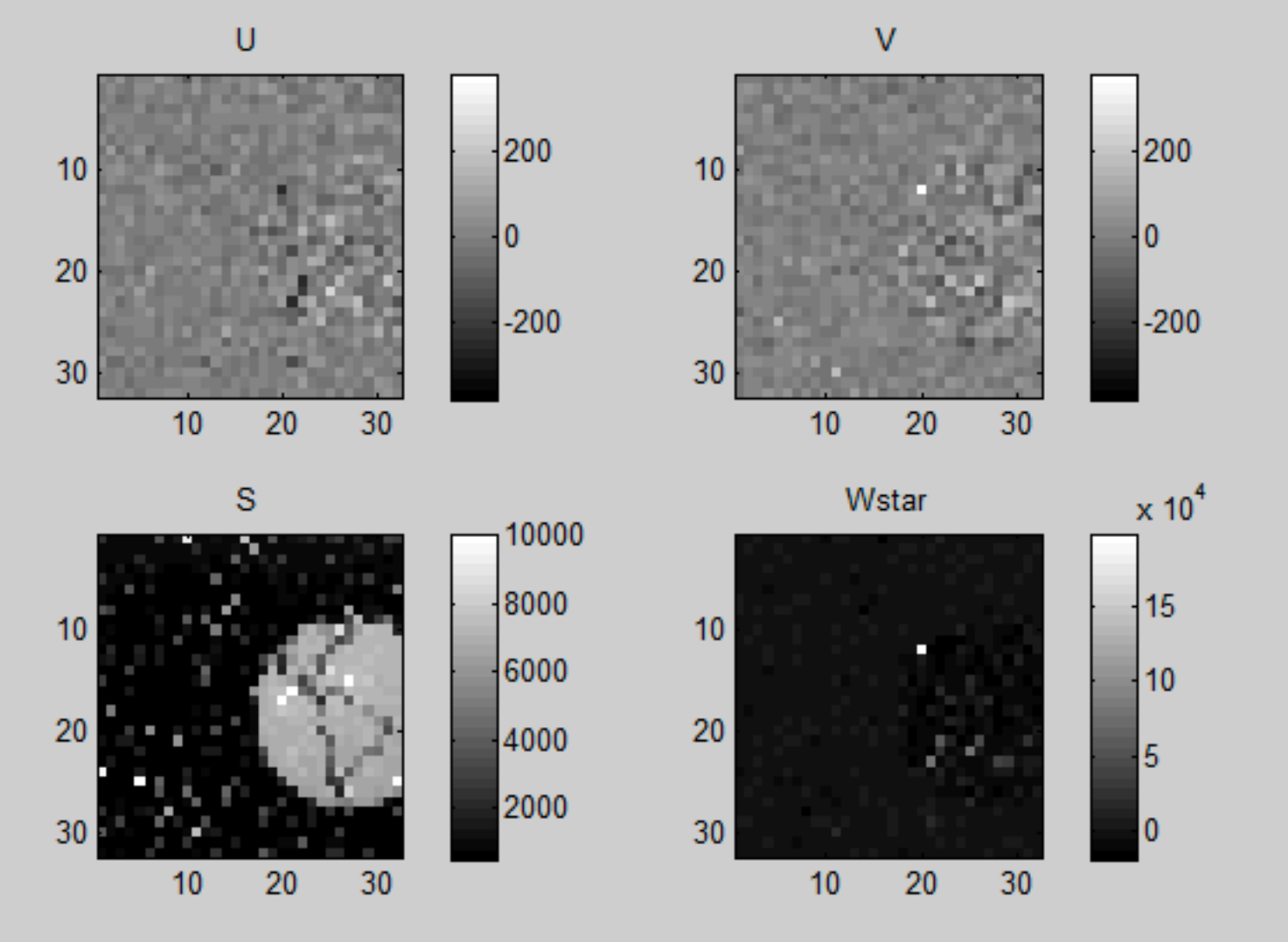


Probability of Missed Acquisition

- **Estimated performance for a 128x128 array**
  - Decreasing per-pixel field-of-view decreases background counts
  - Beacon is optimized to for 2x2 centroid

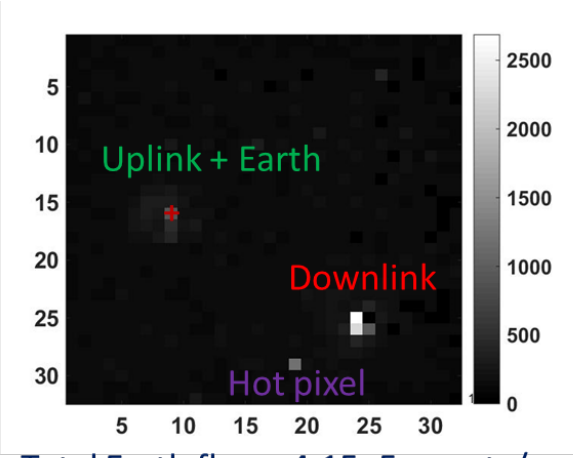


Earth Image Subtraction

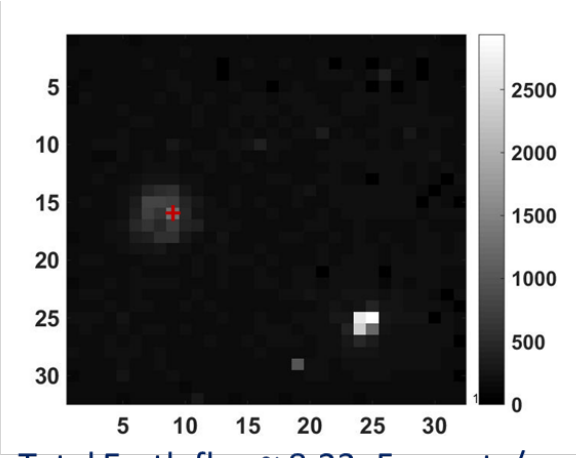


Up-counter Statistics for Varying Earth Upwelling

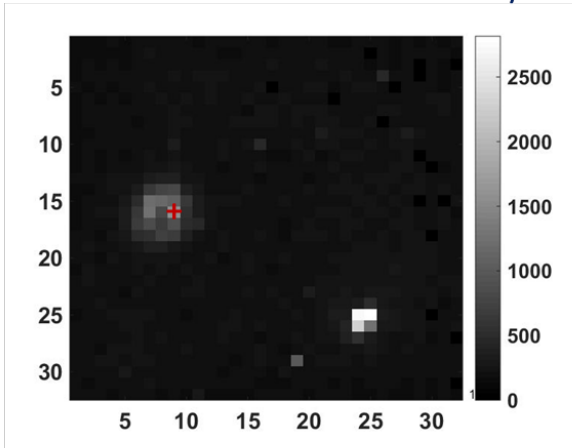
- **Emulated full-Earth using LED/pinhole setup**
  - Sum count uplink beacon centroid with Earth radiance is biased in direction of Earth centroid



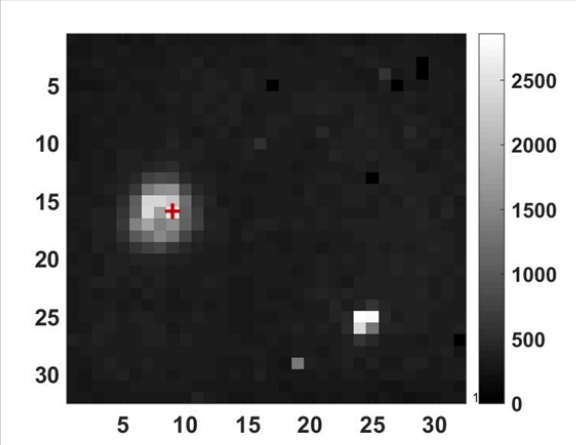
Total Earth flux ~ 4.15e5 counts/sec



Total Earth flux ~ 8.23e5 counts/sec



Total Earth flux ~ 1.13e6 counts/sec

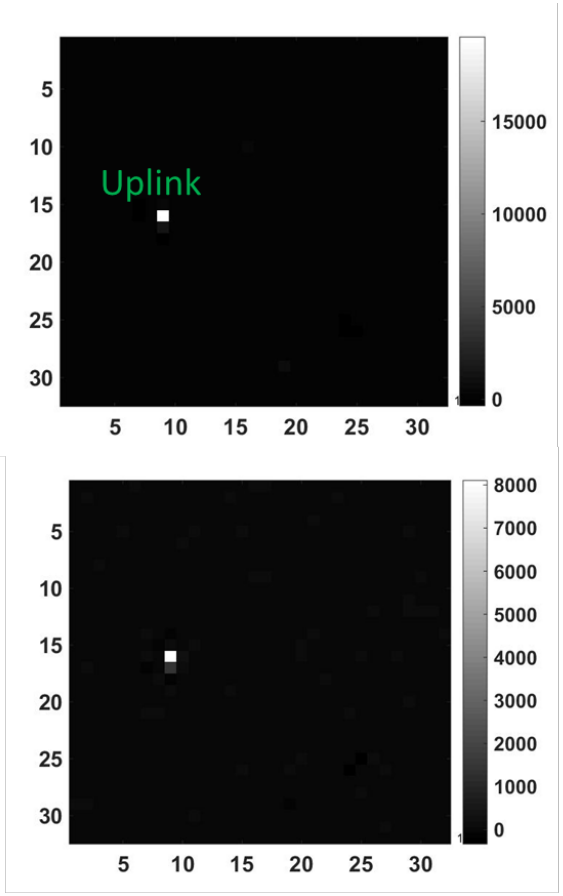


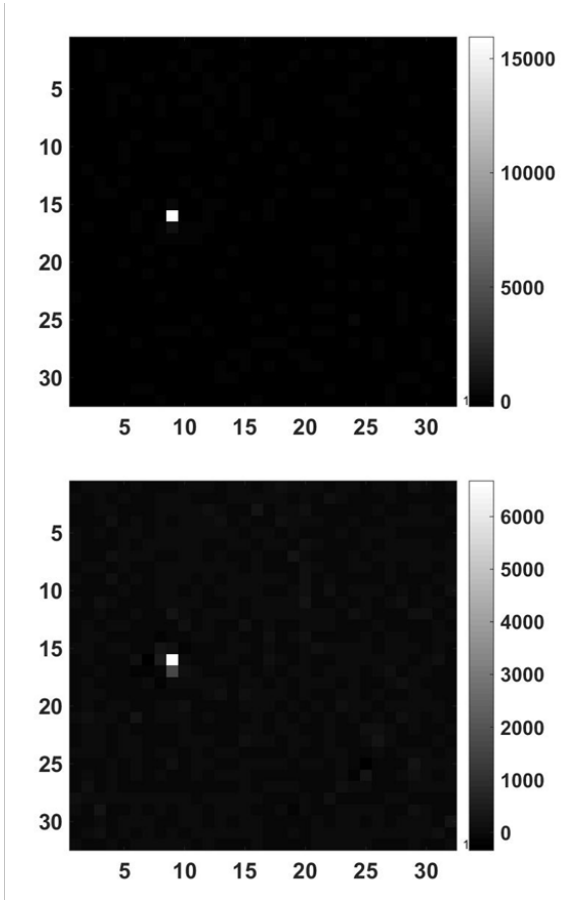
Total Earth flux ~ 2.26e6 counts/sec

From 2.7 AU with 1 nm filter: estimated total Earth flux ~ 1.5e6 - 2e6 counts/sec

Modified Square-law Statistics

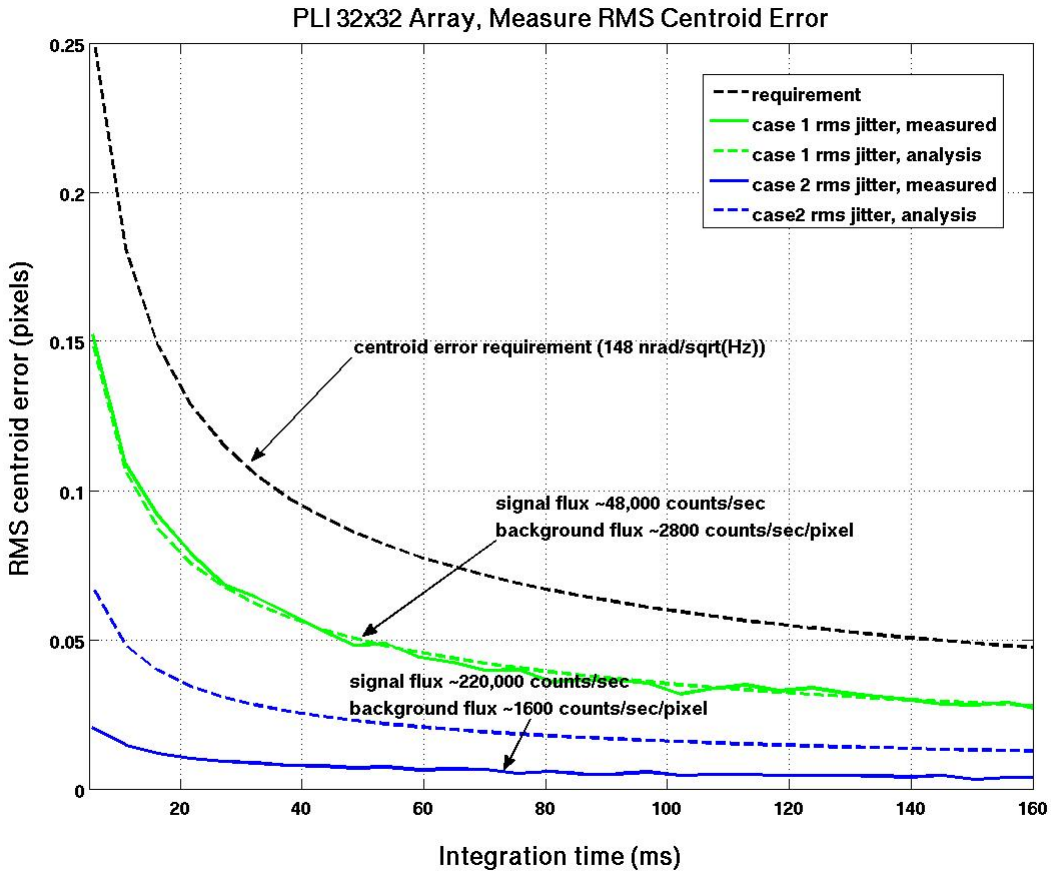
- **Emulated full-Earth using LED/pinhole setup**
  - Modified square-law (MSQ) centroid using up-down counts greatly reduces bias at expense of higher noise-equivalent angle jitter due to squaring noise





From 2.7 AU with 1 nm filter: estimated total Earth flux ~ 1.5e6 - 2e6 counts/sec

Beacon Centroid Error



100,000 counts per second corresponds to 0.047 pW at the 1064 nm beacon wavelength at 40% detection efficiency, or about 2.5 pW/m^2 into 22 cm aperture, assuming a 3 dB throughput loss

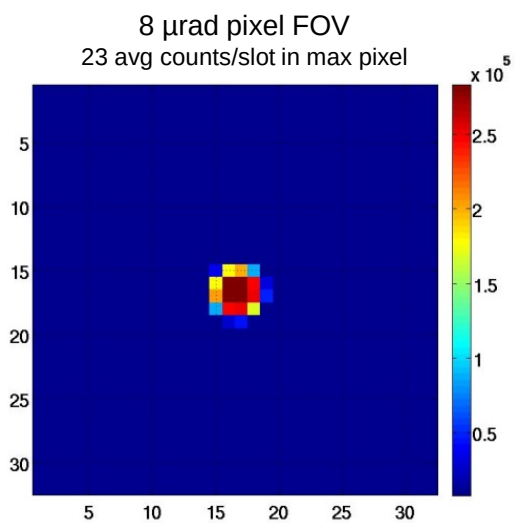
- **In low background conditions, measured centroid jitter < 0.01 pixel for update rates < 15 Hz**
- **High signal flux case shows limitation of read-out saturation due to blocking loss**
  - Actual signal flux is higher than estimate formed by detector output

Impact of Blocking

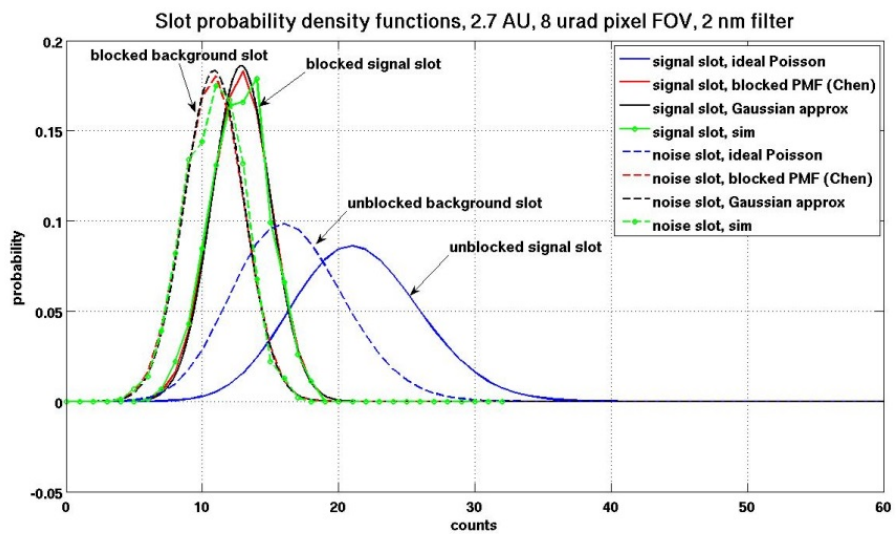
- **Blocking impacts acquisition /tracking performance under high flux conditions**
- **For a fractional slot blocking time of δ, slot counts are approximately Gaussian with**

$$E[K_{blocked}] = \frac{K_{unblocked}}{1+\delta K_{unblocked}} \text{ and } Var[K_{blocked}] = \frac{K_{unblocked}}{(1+\delta K_{unblocked})^3}$$

- **Saturation results in degraded ability to distinguish signal from background, both spatially and temporally**



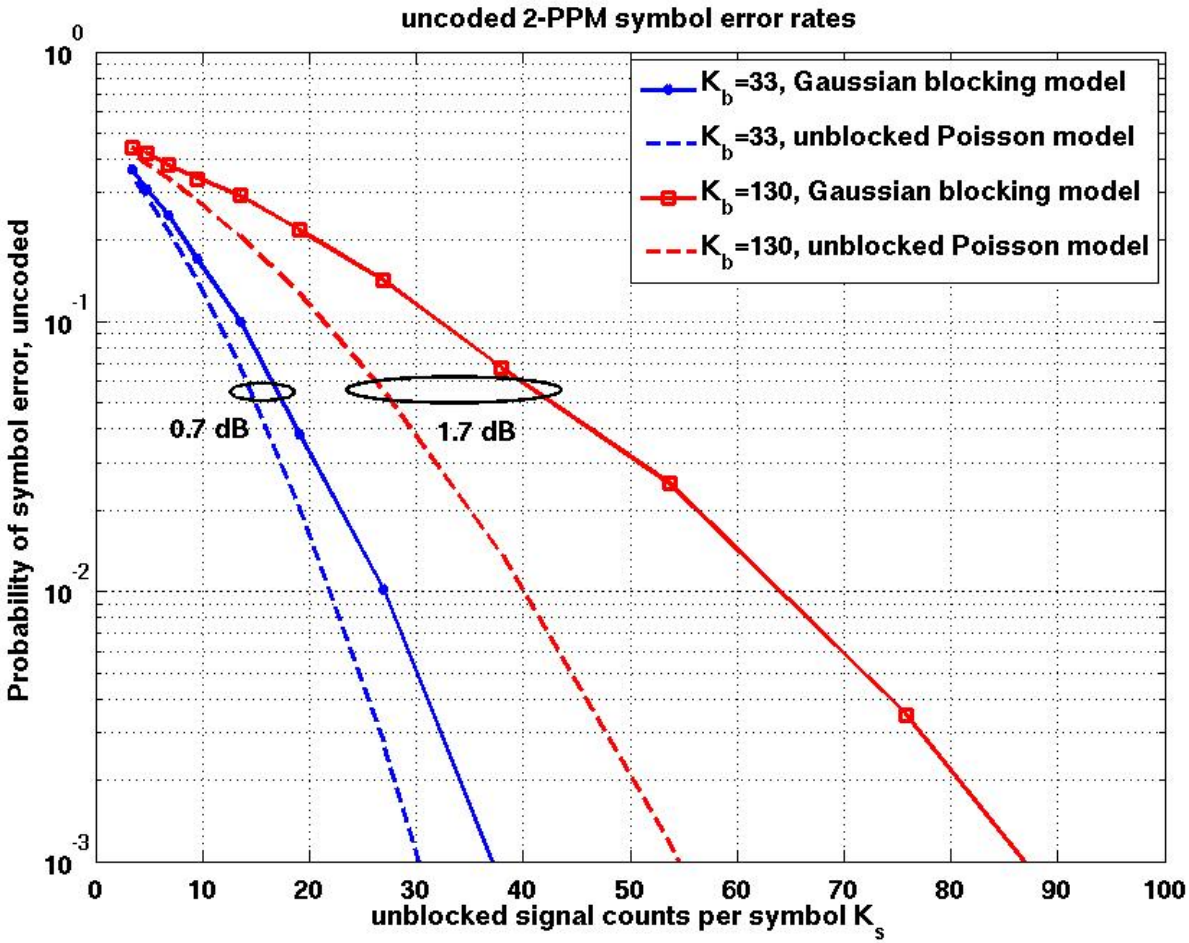
Expected photoelectron flux on 32x32 array (beacon+Earth)



Slot count probability density functions

Blocking impact on low-rate data channel

- **Performed initial evaluation of expected impact of blocking on uncoded error rate for low rate 2-PPM data channel**
  - *Not yet validated with emulation testbed*



Summary

- **Use of photon counting arrays with per-pixel counters allows centroiding performance at the theoretical limits for precision optical beam pointing**
  - *Required laser beacon power for acquisition and tracking can be reduced by a factor of 10 to 100*
  - *Initial performance validation has been performed using real-time signal processing with photon counting camera in testbed environment under emulated background and Earth conditions*
- **High timing resolution of photon counting arrays supports demodulation of optical signals for simultaneous**
  - *Background subtraction*
  - *Data recovery*
  - *Time-of-flight ranging*

The work described here was performed at the Jet Propulsion Laboratory (JPL), California Institute of Technology under contract with the National Aeronautics and Space Administration (NASA)