Photon Counting Detector Array Algorithms for Deep Space Optical Communications

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Outline

- System overview
  - Tracking and communications functions
  - Uplink beacon signal
  - Detector array and readout
- Signal processing algorithms
  - Background subtraction and centroiding
  - Parameter estimation
- Performance results
  - Monte-Carlo simulation
  - Laboratory testing

Beacon-Assisted Optical Tracking

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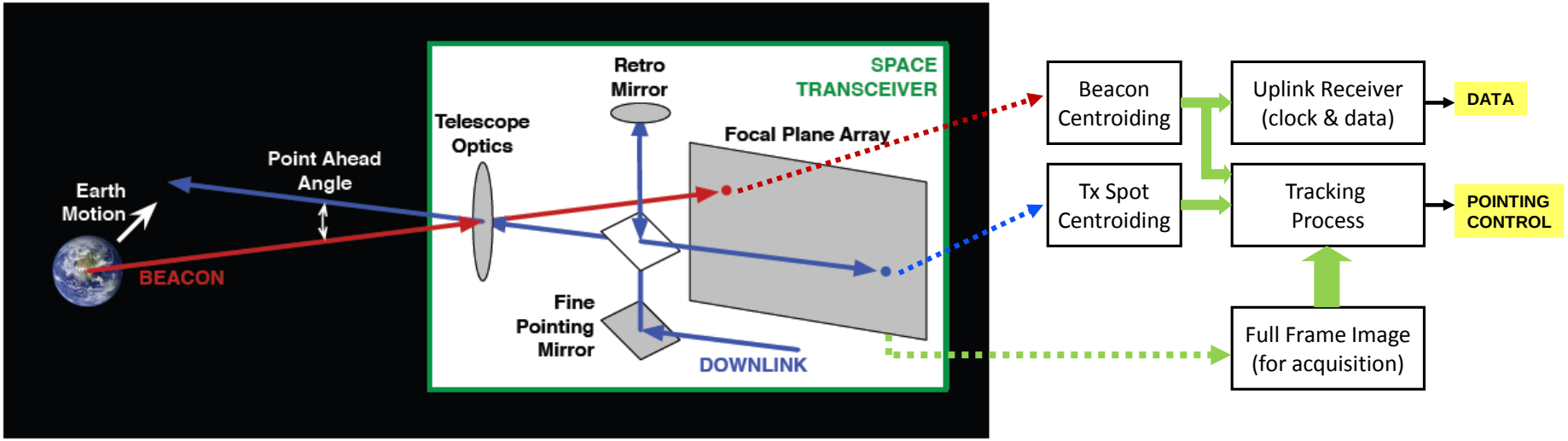
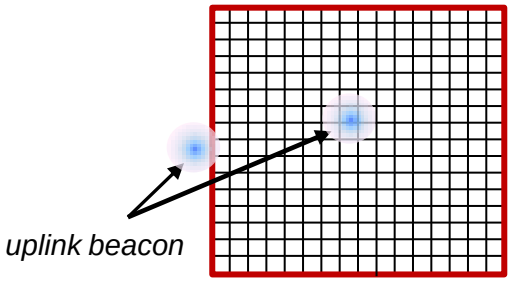


- **Uplink beacon provides reference pointing information without increasing mass of flight transceiver.**
- **Uplink signal position is estimated in order to**
  - **Adjust flight terminal platform attitude and calculate point-ahead angle for downlink transmission**
  - **Acquire and demodulate uplink data**
- **A <u>single</u> detector array reduces alignment errors and optical losses**
  - **Used to estimate location of dim laser beacon to point transmit beam to Earth ground receiver**
  - **Tracks angle of the transmit beam to confirm the point-ahead angle**
  - **Photon counting array has best combination of sensitivity and bandwidth**
- **Signal processing needed for simultaneous spatial acquisition, tracking, parameter estimation and data demodulation**

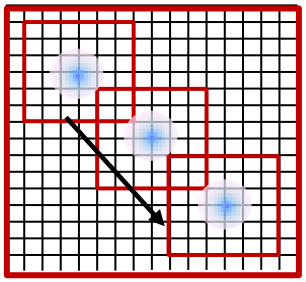
Beacon Processing Modes

1. Uplink beacon detection
   - Use ephemerides to point platform toward Earth. Scan terminal over uncertainty region and search array to determine if beacon is present. Estimate initial detected beacon location.
2. Transit
   - Close platform attitude control loop with centroid estimates from single subwindow and move beacon to designated tracking subwindow.
3. Uplink tracking and downlink point-ahead
   - Maintain beacon position, close beacon control loop with centroid estimates over tracking subwindow.
   - Turn on downlink signal, calculate point-ahead angle, and confirm downlink position using centroid estimates of retro-reflected downlink beam.
   - Demodulate and decode uplink command data.

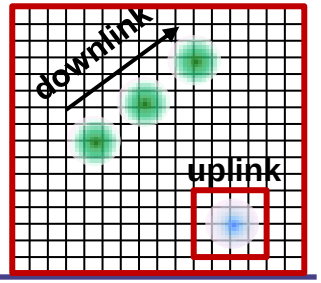
Detection



Transit



Tracking



Uplink Signal Format

- **JPL deep space uplink signal concept uses a nested modulation format consisting of**
  - **Beacon sync pattern: square wave**

  - **Low rate command channel: 2-PPM with 2 intersymbol guard time (ISGT) slots**

  - **Optional high rate data channel: 8-PPM with 4 ISGT slots**

- **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

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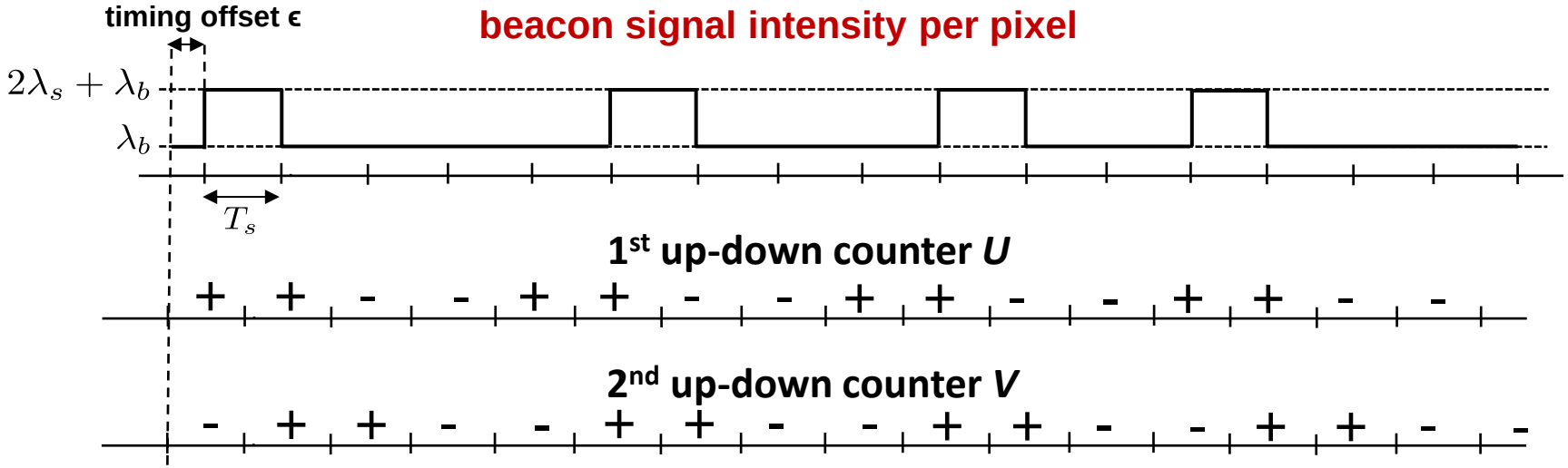
- **Up-down counters alternately increment and decrement pixel counts at beacon frequency**



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

no dependence on background

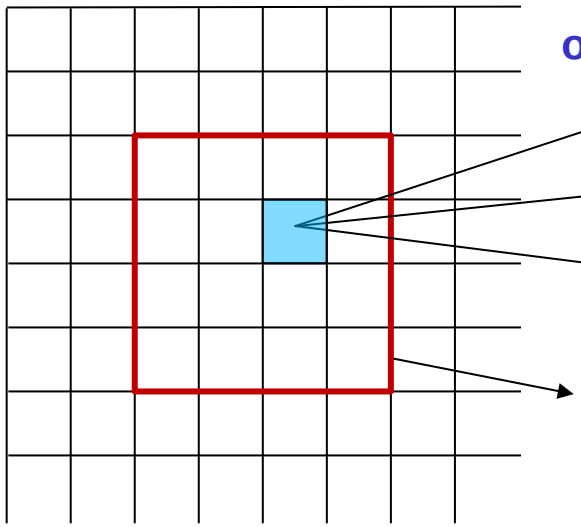
$$E[U] = 4N(1-\epsilon)\lambda_s T_s, \qquad Var[U] = 4N(\lambda_b + \lambda_s)T_s$$

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

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

- **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.**

PCD Array Pixel Processing



output from pixel in *i*th row and *j*th column of subwindow:

- **up-down count 1** $U_{i,j}$
- **up-down count 2** $V_{i,j}$ → $W^*_{i,j} = U^2_{i,j} + V^2_{i,j} - S_{i,j}$
- **up count** $S_{i,j}$

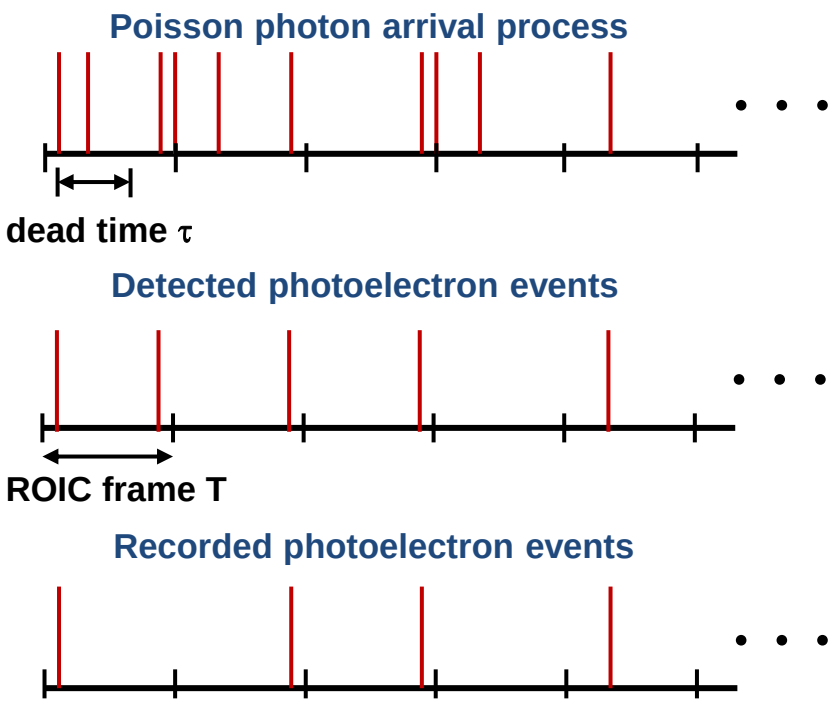
centroid output from subwindow: $\hat{C} = (\hat{x}, \hat{y})$

- **Subwindow centroid estimate** $\hat{C} = (\hat{x}, \hat{y})$ **is calculated using the modified square-law statistics** $W^*_{i,j} = U^2_{i,j} + V^2_{i,j} - 2S_{i,j}$ **:**

$$\hat{x} = \sum_{j=0}^{N_{columns}-1} (j+0.5) \sum_{i=0}^{N_{rows}-1} W^*_{i,j} \quad , \quad \hat{y} = \sum_{i=0}^{N_{rows}-1} (i+0.5) \sum_{j=0}^{N_{columns}-1} W_{i,j}$$

Detector/ROIC Blocking Model

- Blocking limits maximum detectable counts, and comprises two effects
  - Detector dead time – no arrival within τ sec from prior arrival can be detected
  - ROIC frame rate/single photon detection limit – at most one count per frame recorded
- Non-paralyzable blocking model

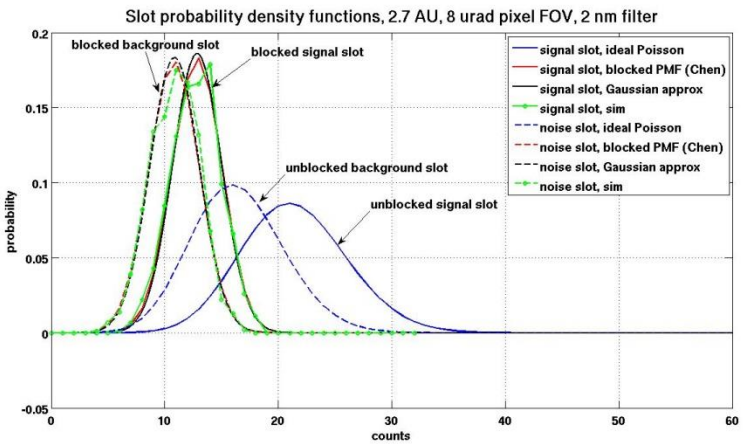


- Detector dead time depends upon adjustable quenching parameter (typically >0.5 μs)
- ROIC frame time is also on microsecond time scale
- We combine both effects into one with blocking time τ = 2.048 μs

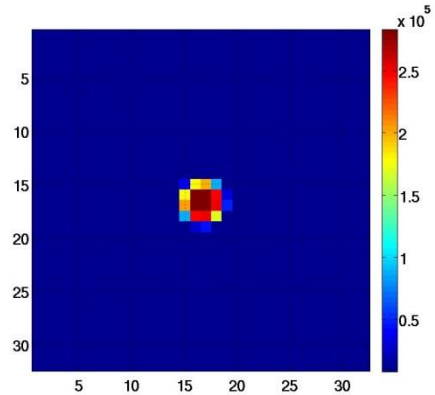
Impact of Blocking

- **Per pixel blocking time of 2.048 μs (equivalent to ROIC frame time)**
- **Uplink signal slot duration = 65.536 μs → fractional slot blocking time of 0.03**
- **Effect of blocking on 2-PPM link performance is minimal for this dead time ratio, *under low flux conditions* (Chen, Stephens, Boroson)**
- **Blocking impact on acq/tracking error must be evaluated under high flux conditions.**
- **For a fractional slot blocking time of δ, slot counts are approximately Gaussian with**

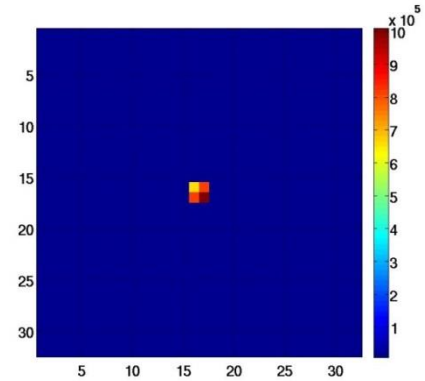
$$E[K_{blocked}] = \frac{K_{unblocked}}{1+\delta K_{unblocked}} \text{ and } Var[K_{blocked}] = \frac{K_{unblocked}}{(1+\delta K_{unblocked})^3}$$



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



8 μrad pixel FOV
23 avg counts/slot in max pixel



32 μrad pixel FOV
73 avg counts/slot in max pixel

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

Monte Carlo Simulation

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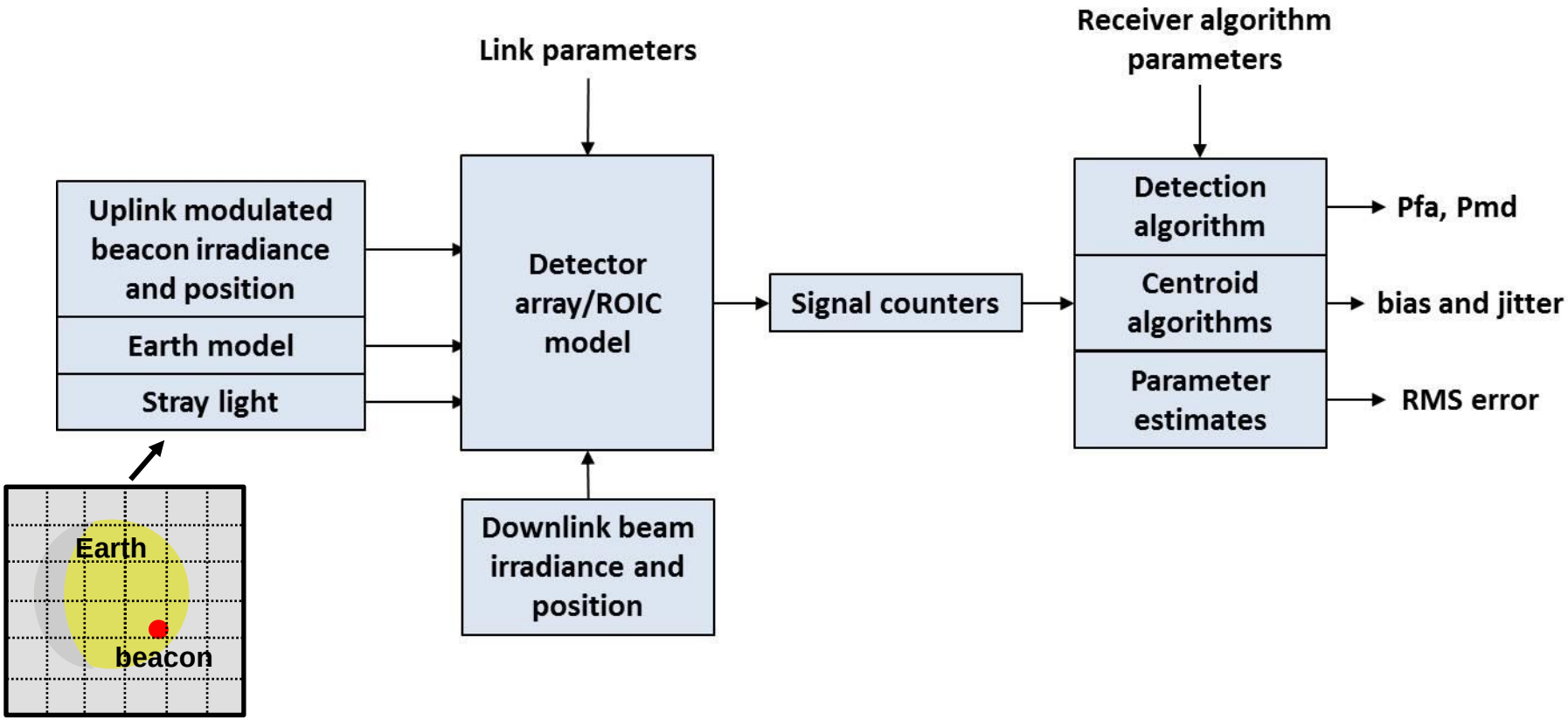
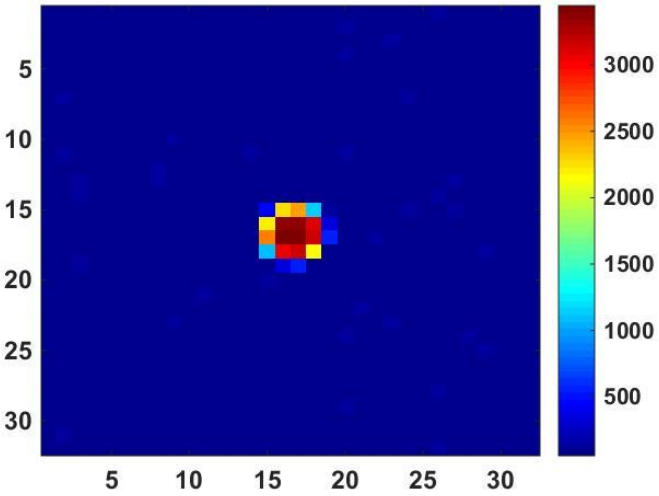
- Single photon counting detector array model and signal processing simulated in software
- Model assumptions
  - Gaussian signal beam, uniform Earth radiance, uniform dark flux and detection efficiency
  - No pixel crosstalk
  - Unblocked Poisson arrivals or Gaussian blocking model

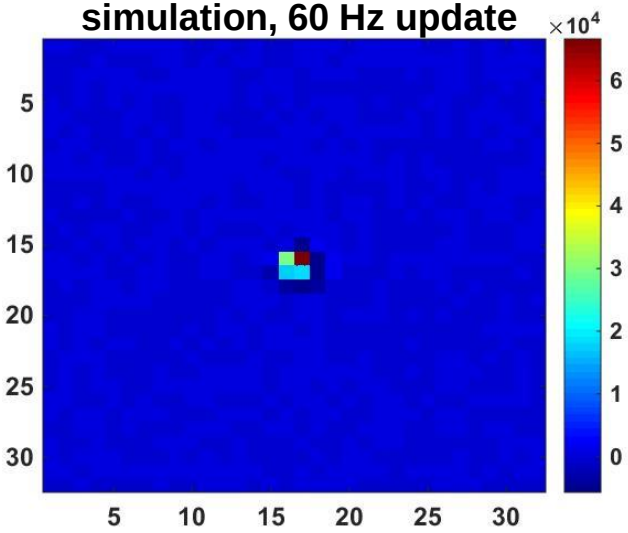


Signal Detection

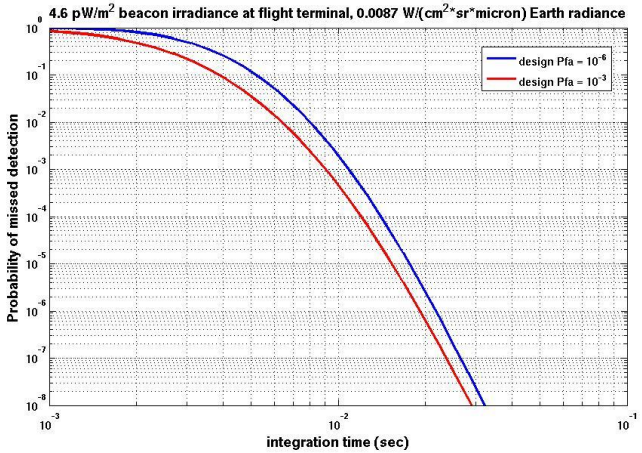
Up-count statistics (UC, sum)
simulation, 60 Hz update



Modified square-law statistics (MSQ)
simulation, 60 Hz update



Probability of missed detection



- Pixel modified square-law statistics are used to distinguish modulated signal from background
- Statistic from maximum pixel is compared to threshold to detect signal
- For Mars far-range case, statistic integration time of 20 - 40 msec is sufficient to achieve 10^{-6} probability of missed detection
- In practice, platform stability will limit integration time

Uplink Beacon Centroiding

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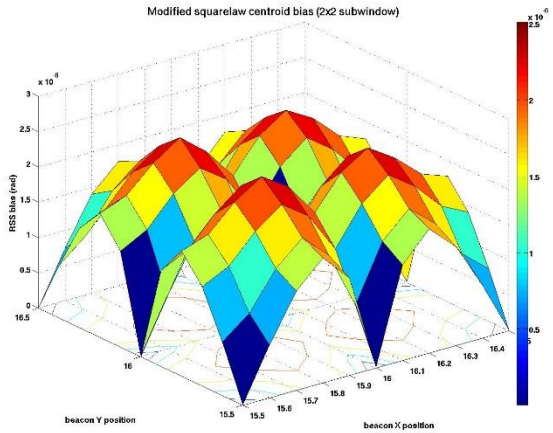
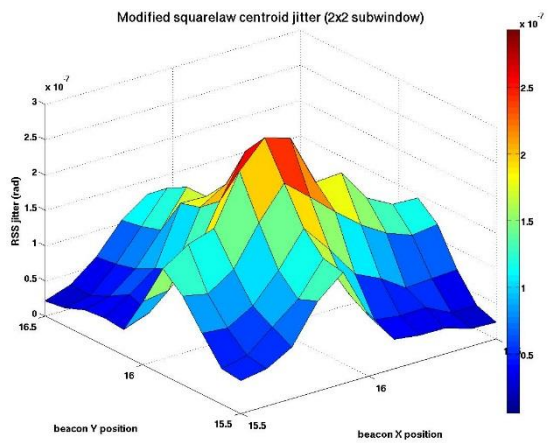
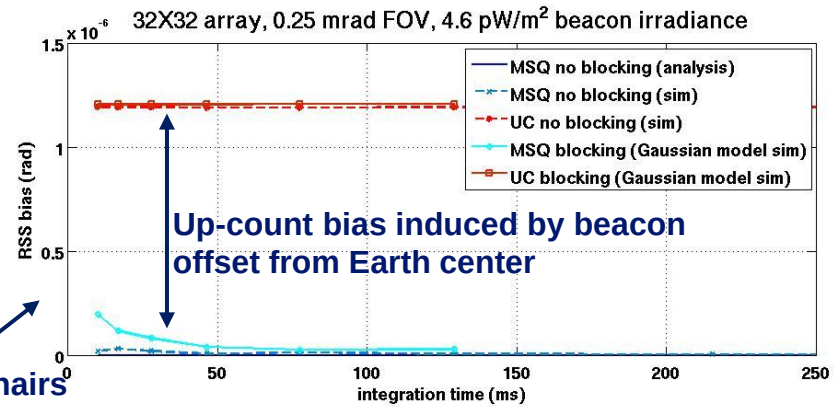
- Centroid bias and jitter varies as beacon position within pixel changes
- Up count centroid has high bias and low jitter; MSQ centroid has low bias and high jitter
- Blocking degrades centroiding performance

Expected MSQ centroid bias

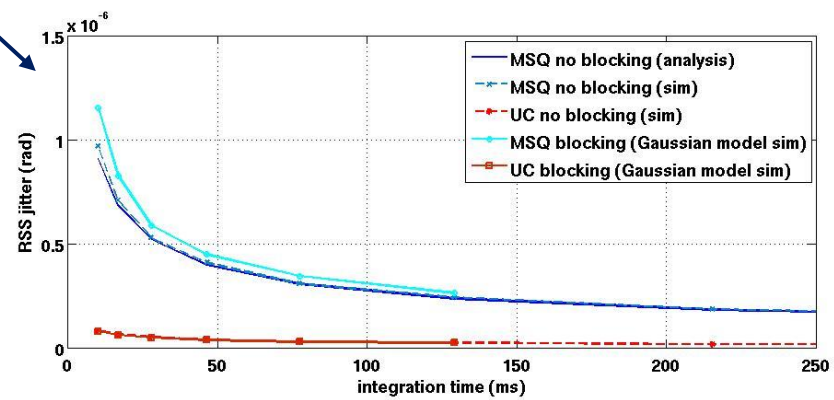


Expected MSQ centroid jitter



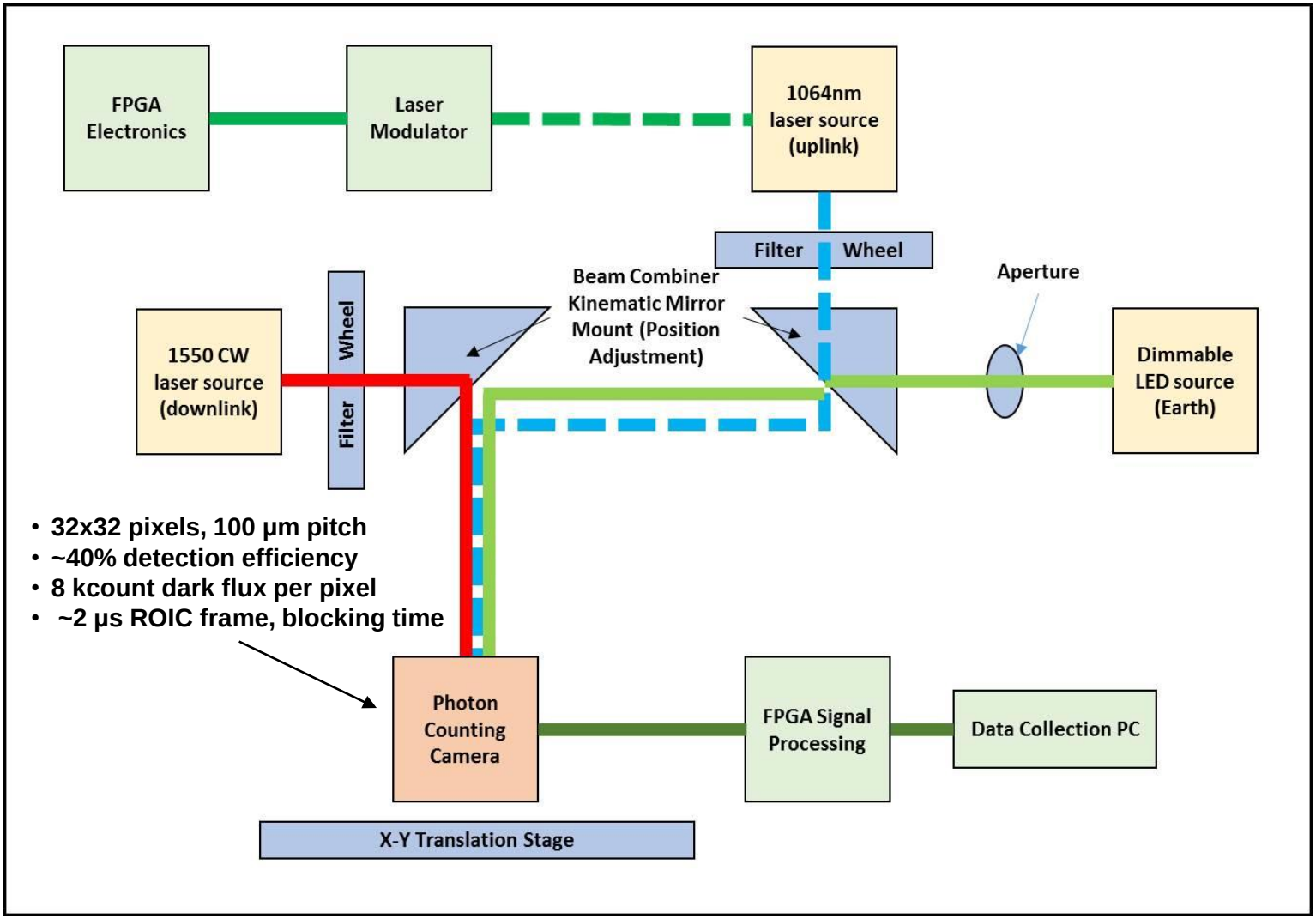


Beacon in crosshairs of 2x2 pixel window



Laboratory Testing

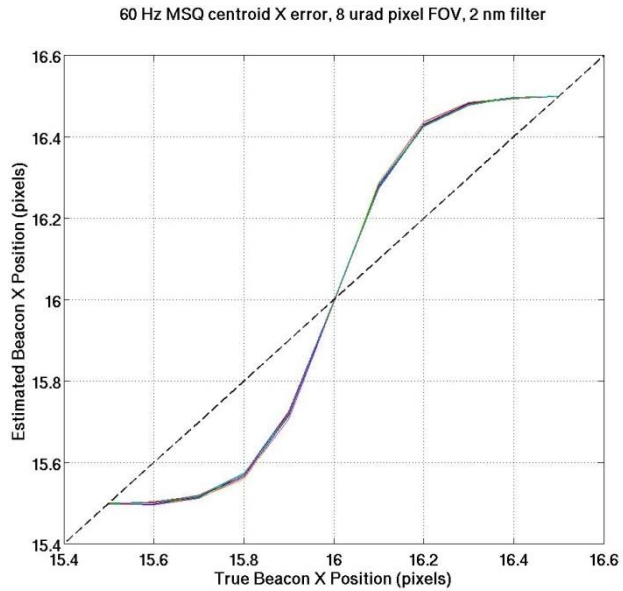
Photon counting camera testbed used to conduct static testing of detector and algorithm performance



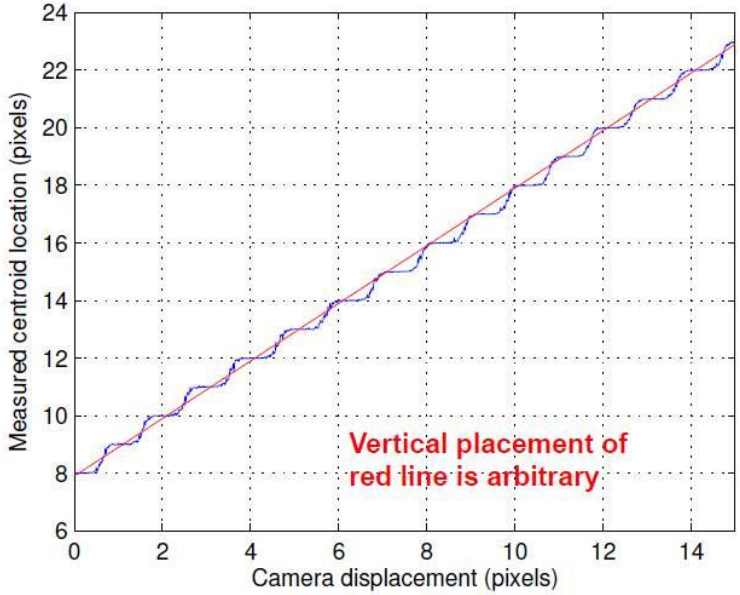
Centroid Characteristic

- **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



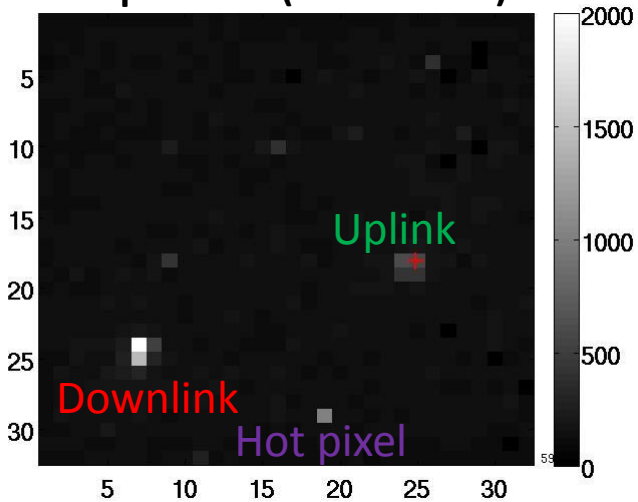
Measured centroid v. beacon displacement



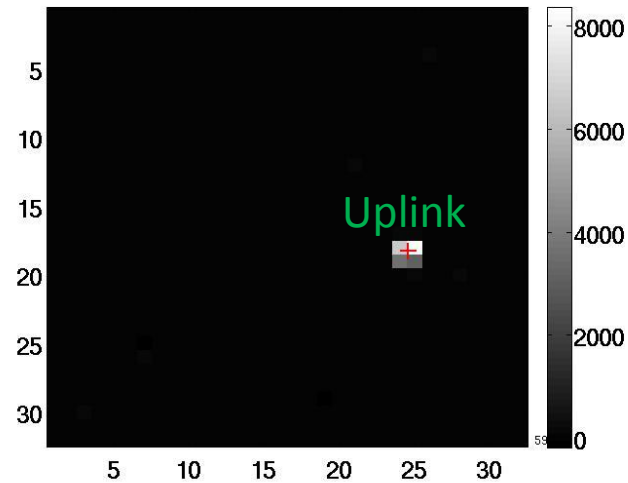
Laboratory Centroid Measurements

no Earth background, estimated total beacon flux ~97,000 counts/sec

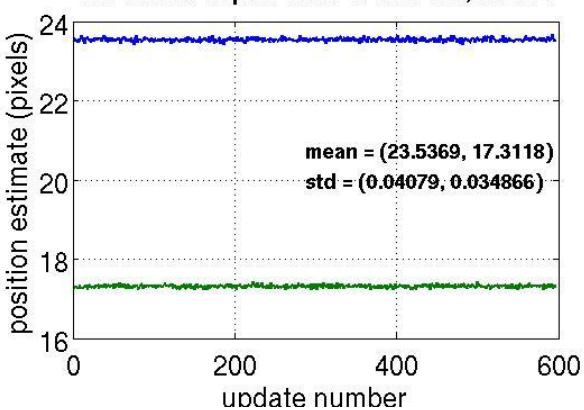
Up counts (sum counts)



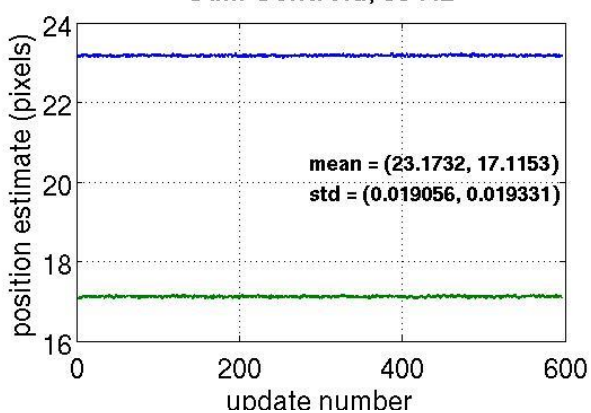
MSQ statistic



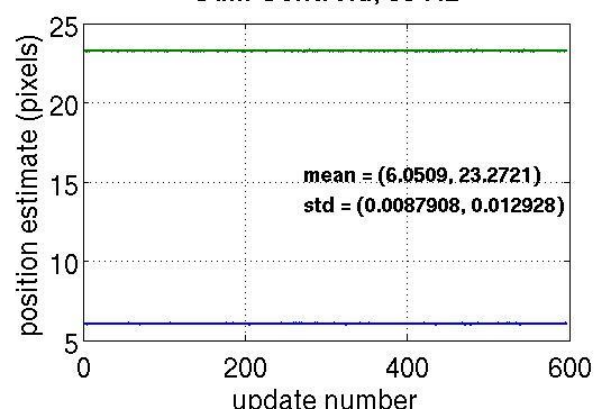
Uplink
Modified Squarelaw Centroid, 60 Hz



Uplink
Sum Centroid, 60 Hz



Downlink
Sum Centroid, 60 Hz



Laboratory Centroid Measurements

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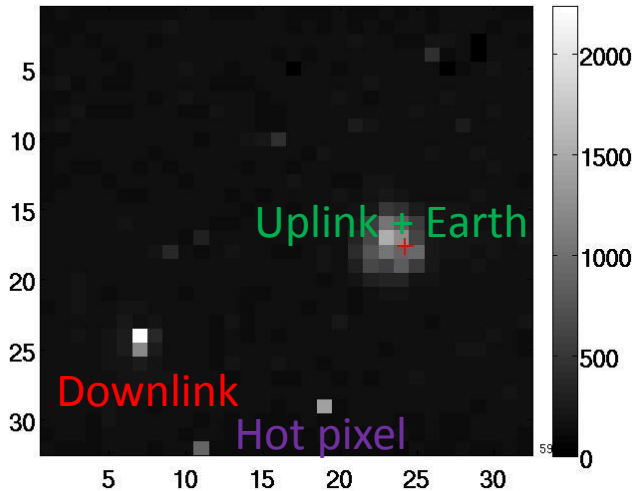
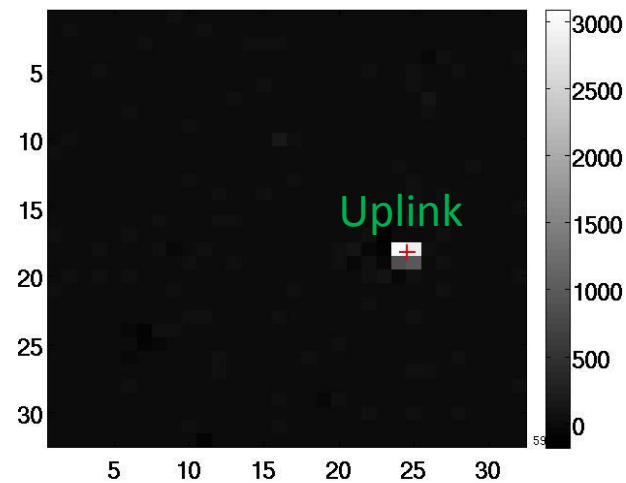
estimated Earth flux per pixel ~98,000 counts/sec/pixel

Up counts (sum counts)

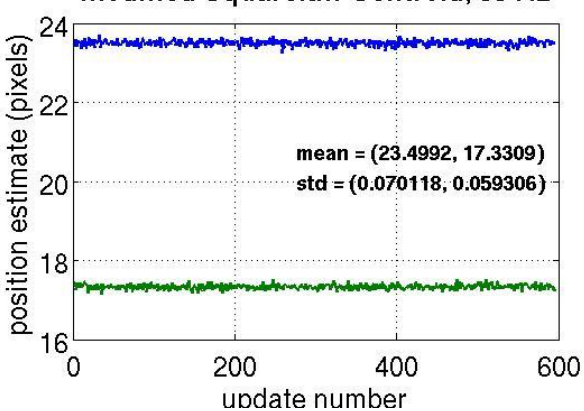


MSQ statistic



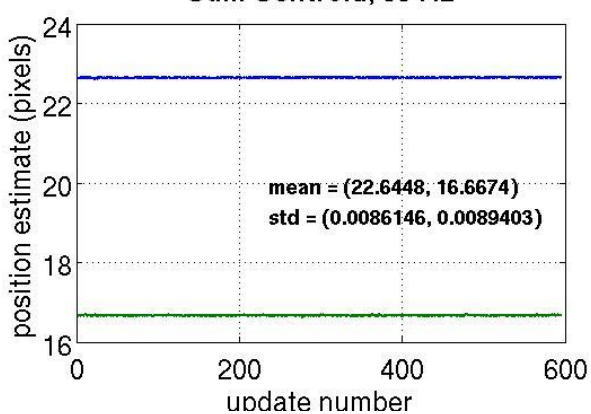
Uplink

Modified Squarelaw Centroid, 60 Hz



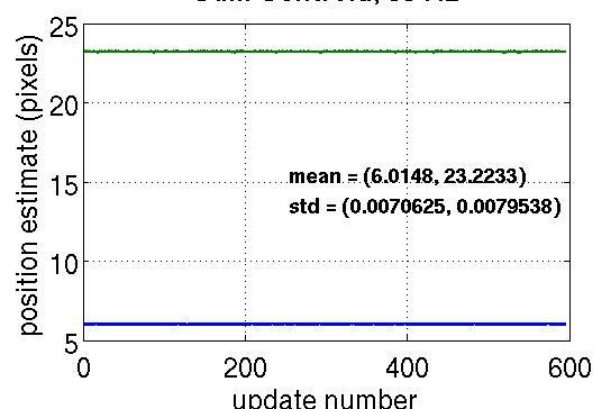
Uplink

Sum Centroid, 60 Hz



Downlink

Sum Centroid, 60 Hz



Laboratory Centroid Measurements

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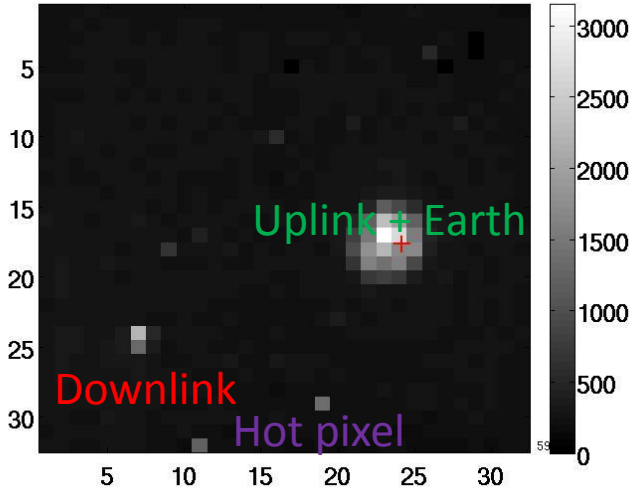
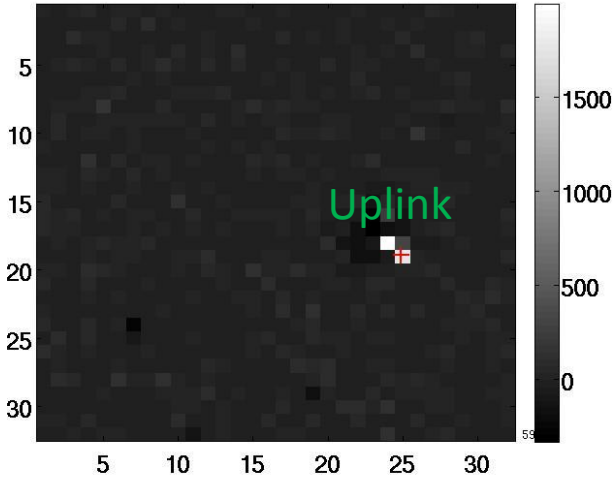
estimated Earth flux per pixel ~203,400 counts/sec/pixel

Up counts (sum counts)

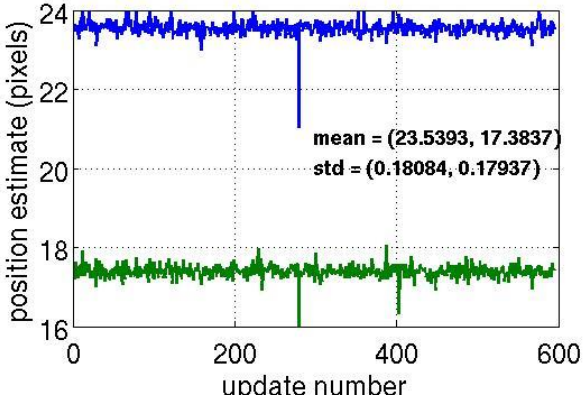


MSQ statistic



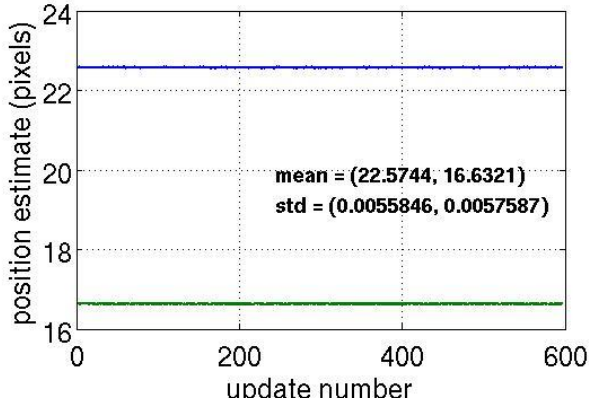
Uplink

Modified Squarelaw Centroid, 60 Hz



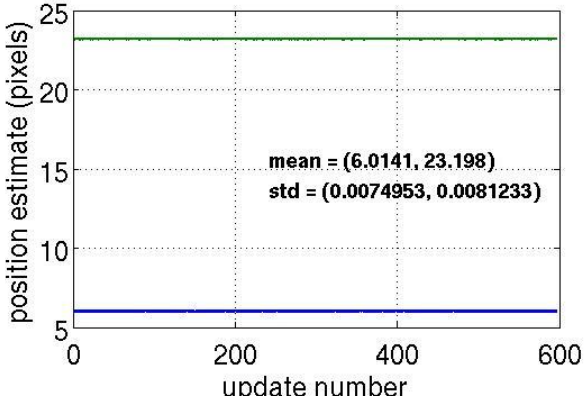
Uplink

Sum Centroid, 60 Hz

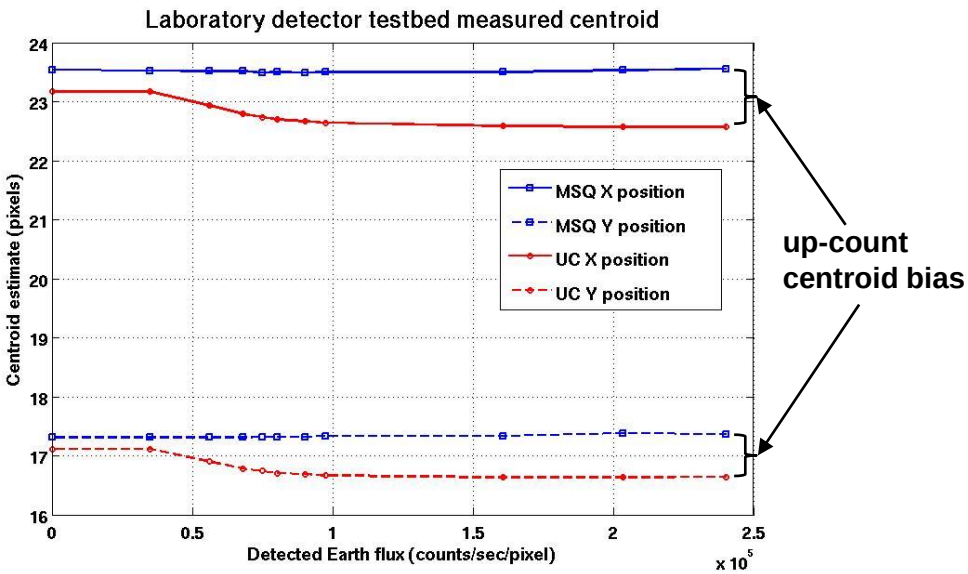


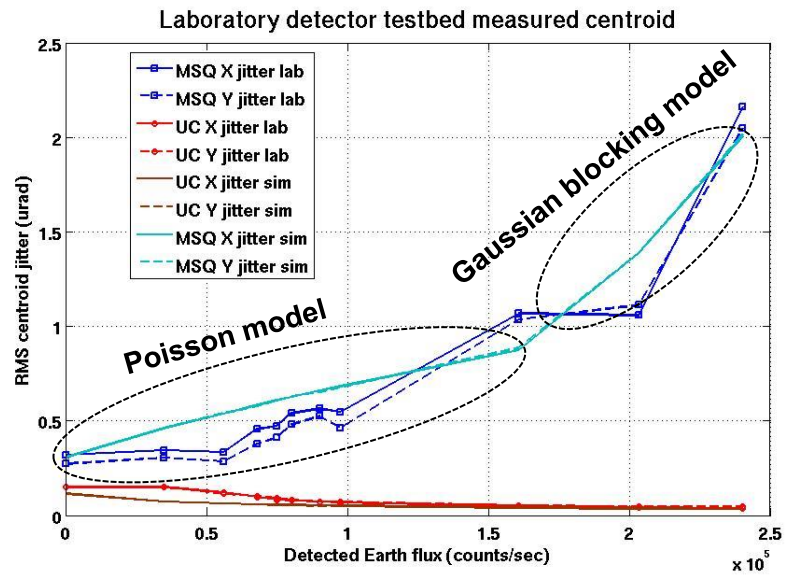
Downlink

Sum Centroid, 60 Hz



Performance Results





- Uplink UC centroid changes as Earth flux increases, MSQ centroid does not
- MSQ centroid jitter increases with increasing Earth flux
  - At <1.5e5 Earth counts/sec/pixel, per axis jitter < 1 µrad
- Earth-beacon centroid difference ~ 1 pixel in X, ~0.75 pixel in Y (8 µrad, 6 µrad)
- Earth flux per pixel for Mars 2.7 AU ~1.6e5 counts/sec/pixel (assuming 1 nm filter, 3 dB optical losses, 40% DE, irradiance of 0.0087 W/m^2/sr/µm)
- Measured values track simulation results using Gaussian blocking model
- Downlink jitter < 0.16 µrad per axis
- Additional results with better calibrated measurements expected in next few months

Summary

- Developed beacon detection and centroiding algorithms for deep space optical transceiver acquisition and tracking using a flight-like photon counting detector array
- Demonstrated real-time signal processing with photon counting camera in testbed environment emulating background and Earth conditions
- Evaluated algorithms using total flux (up) and background-subtracting (modified square law) pixel statistics with modulated beacon
  - Modified square law statistics enable accurate signal detection and position estimation in presence of strong background
  - Analysis and simulation results based upon estimated channel parameters and blocking models demonstrated good fit to experimental data
  - Demonstrated sub-microradian centroiding accuracy sufficient for deep-space downlink pointing
- Further work required to characterize system level performance
  - New detector array with integrated microlenses in next 3-4 months
  - Integration with vibration isolation platform and closed loop platform control in next year