Photon Counting Arrays for Deep Space Optical Beacon Acquisition and Tracking

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- Application
- Detector Array Readout
- Path Forward

Why Optical Communications?

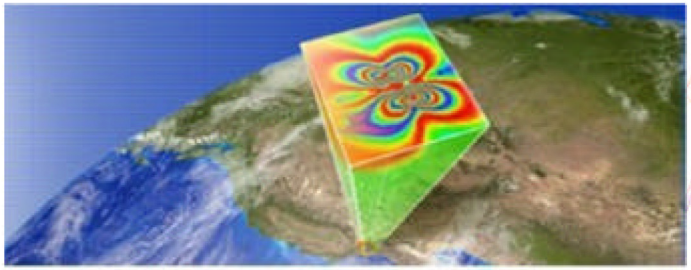
➢ 10 X to 100X increased deep space data returns over present RF communications

- ***Increased science data return***
- ***"Virtual Presence"***
- ***Public engagement***

10X Increased Imaging Resolution for Astrophysics

Human Exploration Beyond Low-Earth Orbit

Future Advanced Instruments

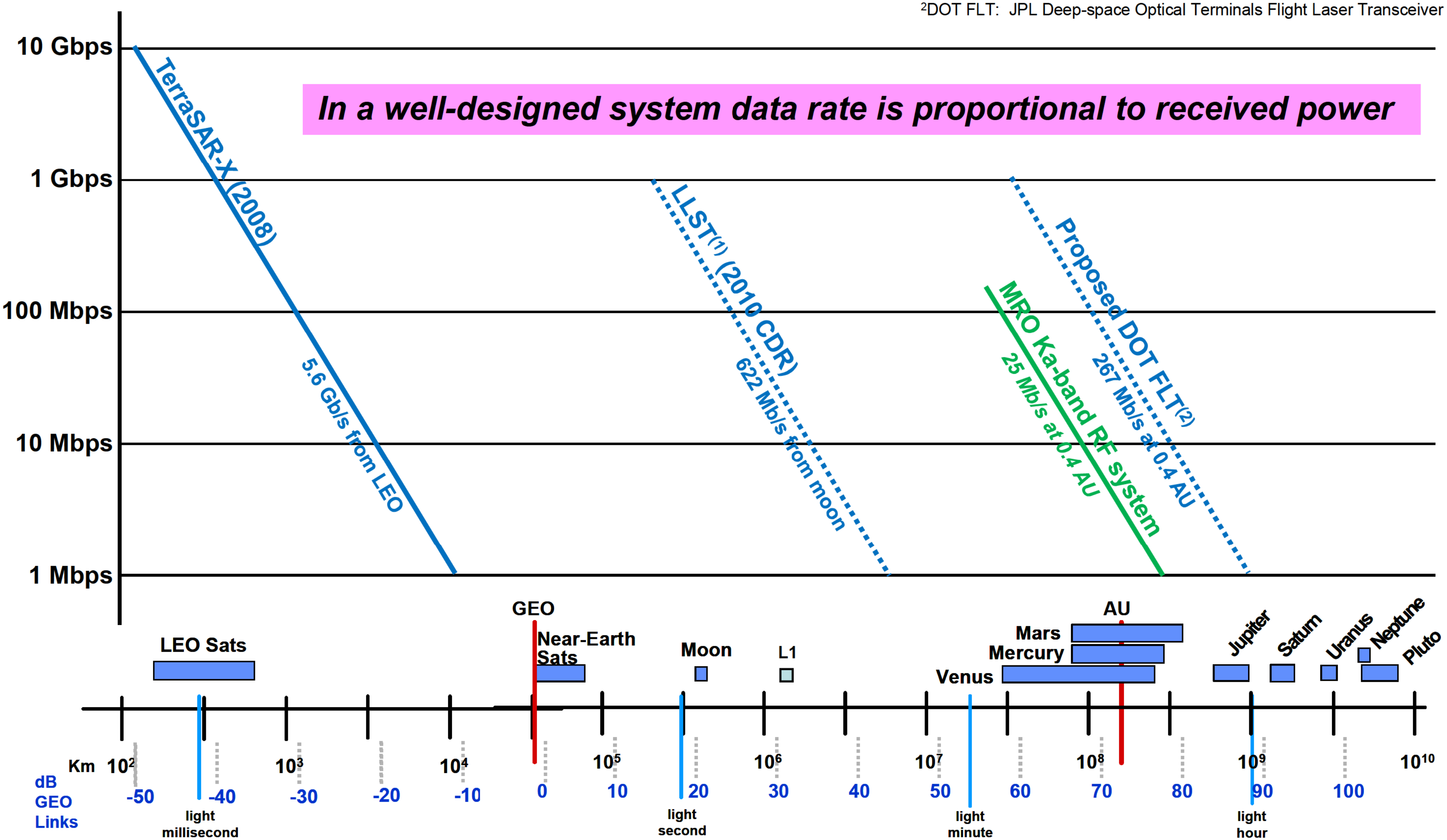


10X Increased Resolution Imaging for Earth Science

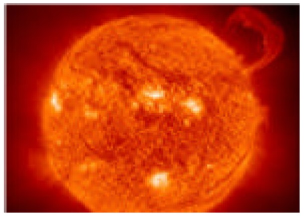
Tele-Presence with Live HiDef Video

Range-Squared Loss

[1]LLCD: MIT-LL Lunar LaserCom Space Terminal,
[2]DOT FLT: JPL Deep-space Optical Terminals Flight Laser Transceiver

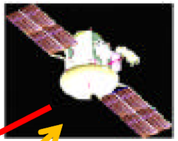


Deep Space Optical Scenario



Sun
Can be in field of view
Primary source of optical noise

REQUIRES:
- Stable / isolated platform
- Efficient uplink detector
- Efficient PPM transmit laser
- Sub-microradian pointing



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

__Downlink__
- Stabilized by disturbance isolation system & uplink beacon tracking
- Gb/s return link data
- Ranging

Point-Ahead Angle
- Depends on the transverse component of the Earth's velocity relative to the spacecraft
- Can be many beam widths in deep space

Earth at T_1+RTLT

REQUIRES
- Multi-kW power uplink lasers
- > 10 m optical receiver apertures
- Efficient downlink detectors

Earth at T_1

__Uplink__
- 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

Deep space optical communications improves over RF performance by:

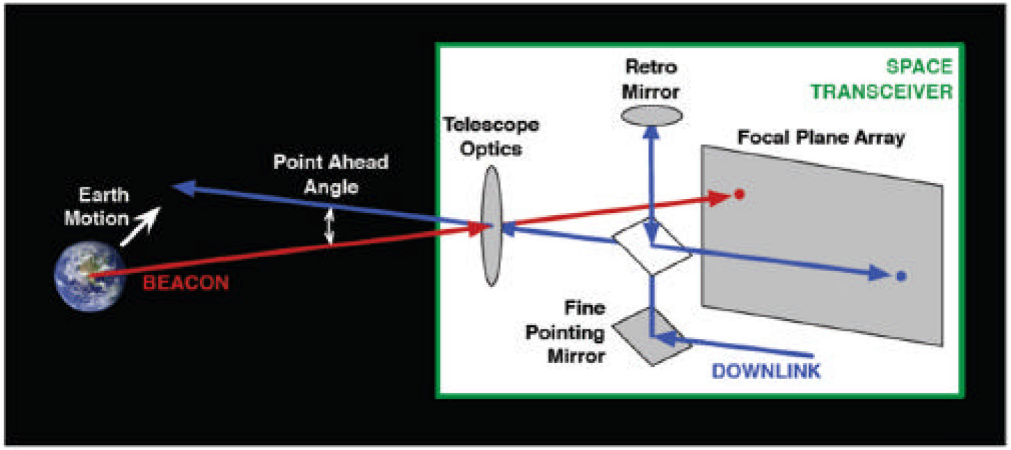
- **Pointing:** Narrow beams from small transmit apertures deliver more power "on target"

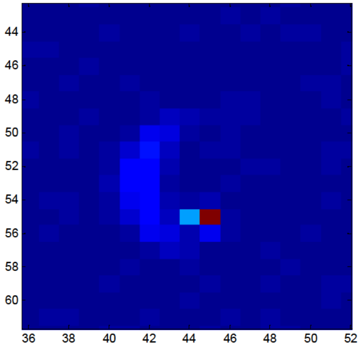
  Beam Width = Wavelength / Antenna Diameter

- **Detection:** Efficient and high rate photon counting "*makes every photon count*"

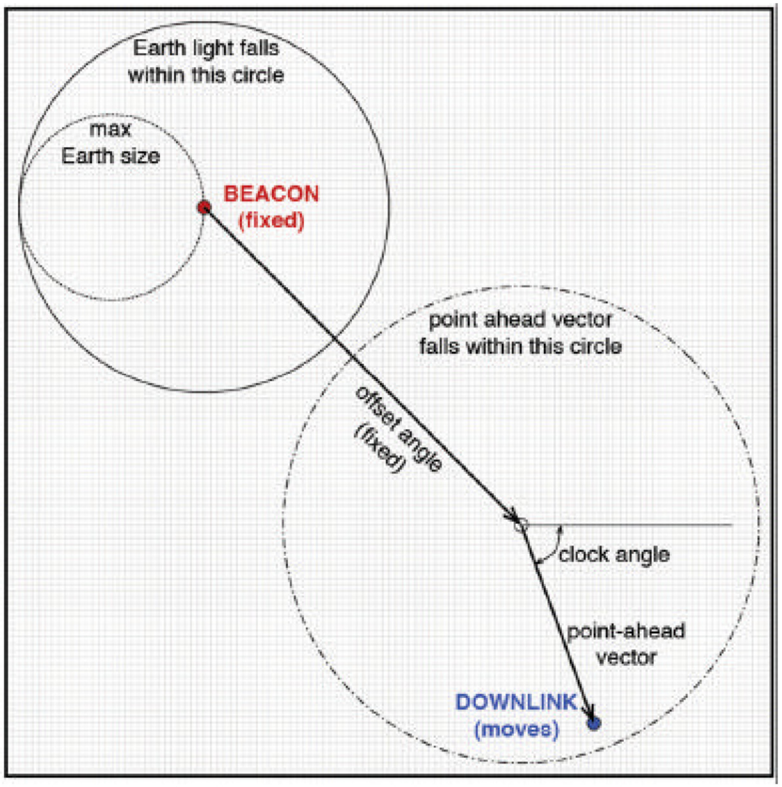
  The optical channel is not thermal noise limited

Transceiver Beam Relationships



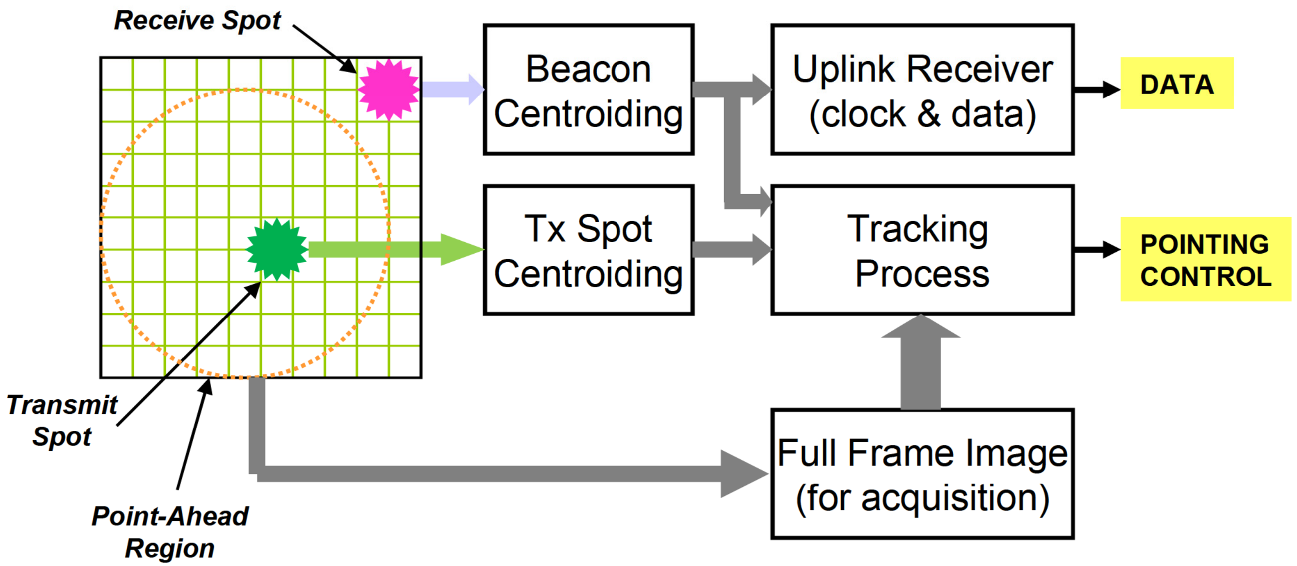


Simulated image of Earth crescent with laser beacon

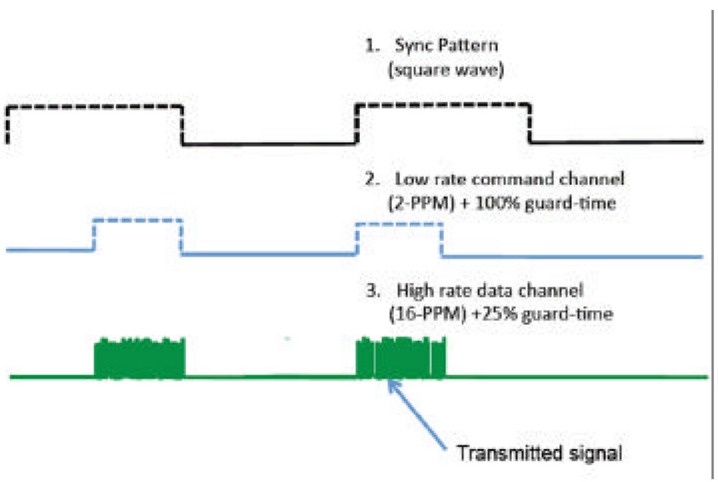


- **A <u>single</u> detector plane minimizes beam alignment errors and optical losses due to splits**
  - Must form an accurate estimate of the location of the dim laser beacon to point the transmit beam to the Earth receiver location
  - Must track the angle of the transmit beam to confirm the point-ahead angle
  - Handshaking with the Earth receiver to confirm pointing in real time is not possible

Acquisition, Tracking, and Data Detector

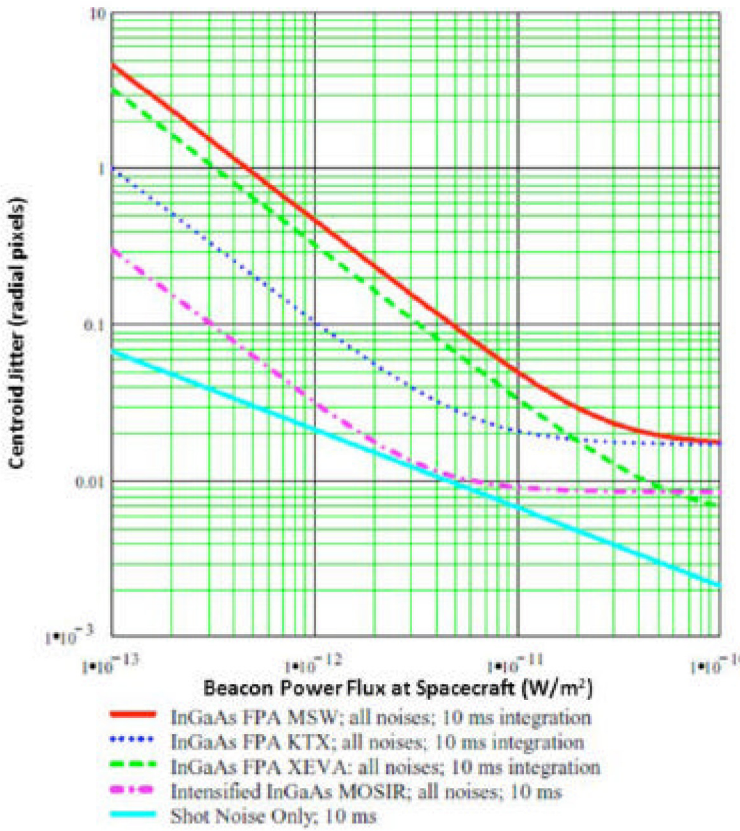


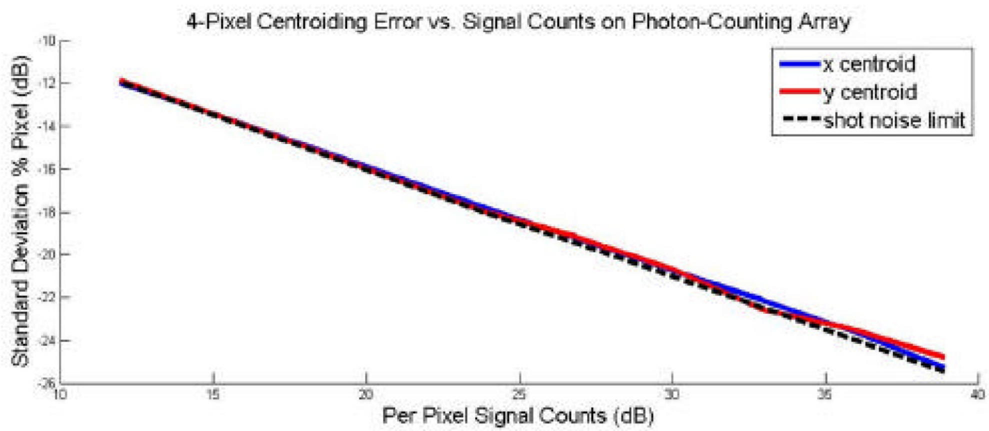
- **Single focal plane receiver architecture for simultaneous acquisition, tracking and uplink data demodulation**
  - Versus two or three typical for an optical receiver design
  - Reduces transceiver mass – Increases transceiver reliability
- **A nested beacon modulation scheme supports background subtraction and multi-rate uplink data**



Analog vs. Photon Counting

- **A significant limitation on uplink beacon estimation accuracy is detector noise**
  – The centroiding performance of an analog focal plane array can be 10 to 100 times poorer than the shot noise limit due to readout noise
- **A focal plane array of single photon detectors (SPD) can achieve shot noise limited performance**
  – Operate with10 to 100 times less beacon transmit power
- **The SPD array can also increases uplink rate from < 100 b/s (Si CCD or InGaAs FPA) to multi-Mb/s**
  – Sub-nanosecond photon arrival timing





- Application
- **Detector Array Readout**
- Path Forward

UPLINK DETECTOR COMPARISONS

- Representative "State-of-the-Art":

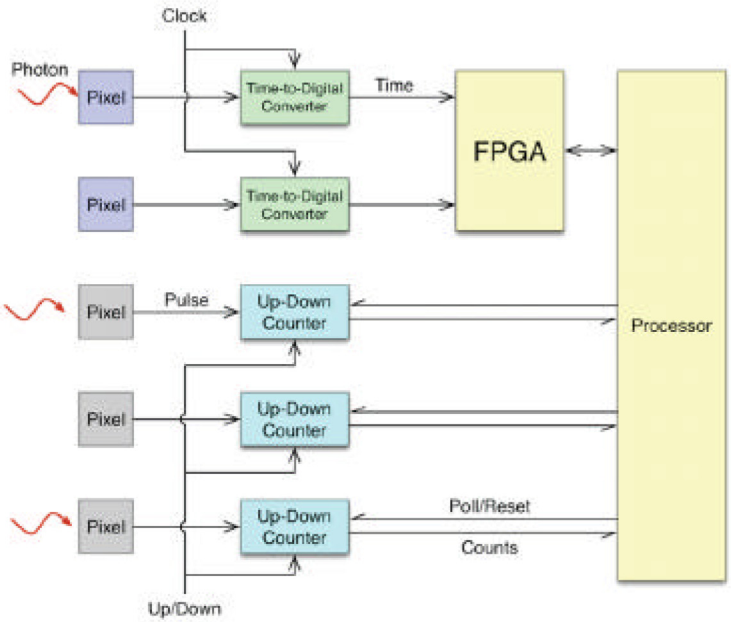
	Geiger Mode			Negative-Avalanche Feedback		Linear Mode
Technology*:	***RCE-Si***	***InGaAsP***	***InGaAs***	***InGaAsP***	***InGaAs***	***HgCdTe***
Efficiency at *1030 nm*	22%	45%	45%	23%	23%	90%
Blocking Loss	0.3 dB	0.8 dB	6 dB	0.1 dB	0.2 dB	*< 1 dB*
Dark Noise / pixel	1 KHz	20 KHz	200 KHz	20 KHz	200 KHz	1 MHz
Timing Jitter	120 ps	270 ps	270 ps	240 ps	240 ps	900 ps
Operating Temperature	250 – 300K	220-270K	200-270K	220-270K	200-270K	80K
DDD (+3dB DCR)	1.3E8 MeV/g	1.0E7 MeV/g		*Assumed equivalent to Geiger Mode*		?
Can Meet 5 yr. Mission Life	Yes	Maybe	Maybe	Maybe	Maybe	Yes
Array Size	32x32	256x256	256x256	32x32	32x32	2x8
TRL	3-4	5	5	3-4	3-4	2-3

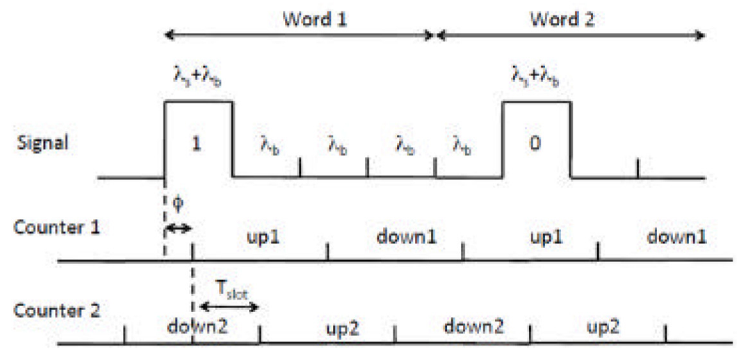
**Sub-band gap Absorption can be used on Si or InGaAsP sensors to detect a 1550 nm transmit beam for point-ahead verification*

The "missing piece" is the application specific read-out integrated circuit (ROIC)

Green – Satisfactory
Yellow – Marginal
Orange – Not quite acceptable
Red - Unsatisfactory

ROIC Pixel Processing





- **The focal plane array is composed of "slow" and "fast" pixels**
  - A 2x2 or larger sub-array of fast pixels is located at the beacon tracking position
- **When the "slow" counters are alternating between the "up" and "down" modes, the background rate has no average effect on the counter state**
  - Conversely, if the counters are run in the "up" mode only, the background rates are preserved

Counter 1:

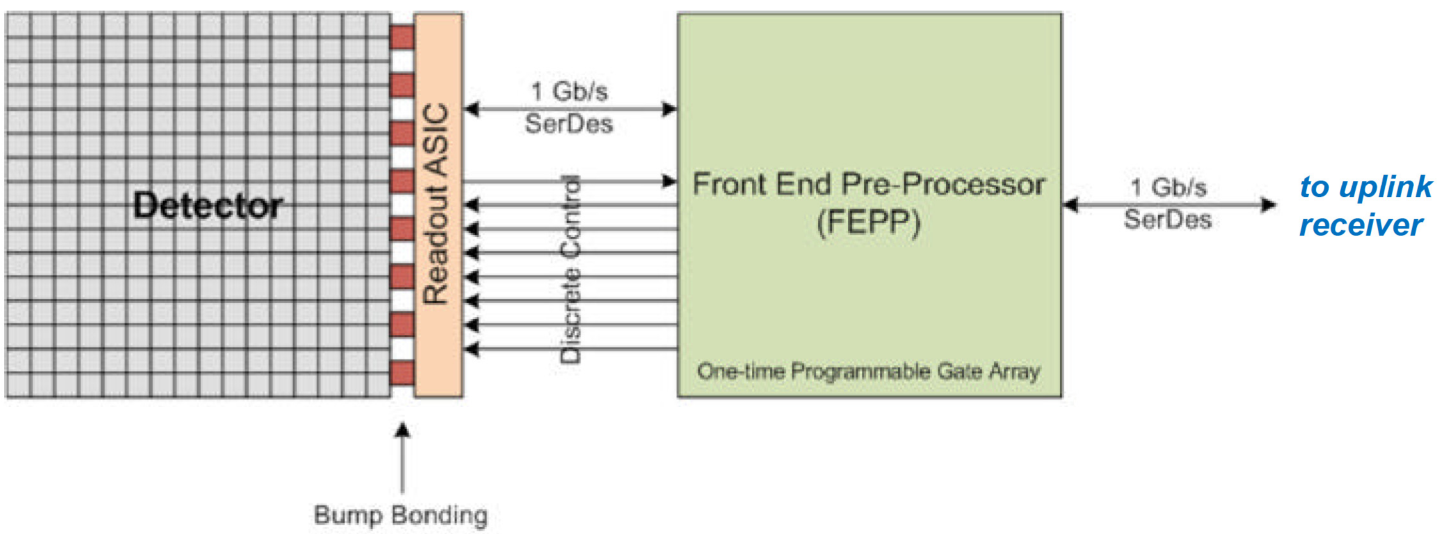
$$\begin{aligned} \langle up \rangle &= 4\lambda_b T_{slot} - \lambda_s \phi + 2\lambda_s T_{slot} \\ \langle down \rangle &= 4\lambda_b T_{slot} + \lambda_s \phi \\ \langle up \rangle - \langle down \rangle &= 2\lambda_s T_{slot} - 2\lambda_s \phi \\ \langle up \rangle + \langle down \rangle &= 8\lambda_b T_{slot} + 2\lambda_s \phi \end{aligned}$$

Counter 2:

$$\begin{aligned} \langle up \rangle &= 4\lambda_b T_{slot} + \lambda_s \phi + \lambda_s T_{slot} \\ \langle down \rangle &= 4\lambda_b T_{slot} - \lambda_s \phi + \lambda_s T_{slot} \\ \langle up \rangle - \langle down \rangle &= 2\lambda_s \phi \\ \langle up \rangle + \langle down \rangle &= 8\lambda_b T_{slot} + 2\lambda_s \phi \end{aligned}$$

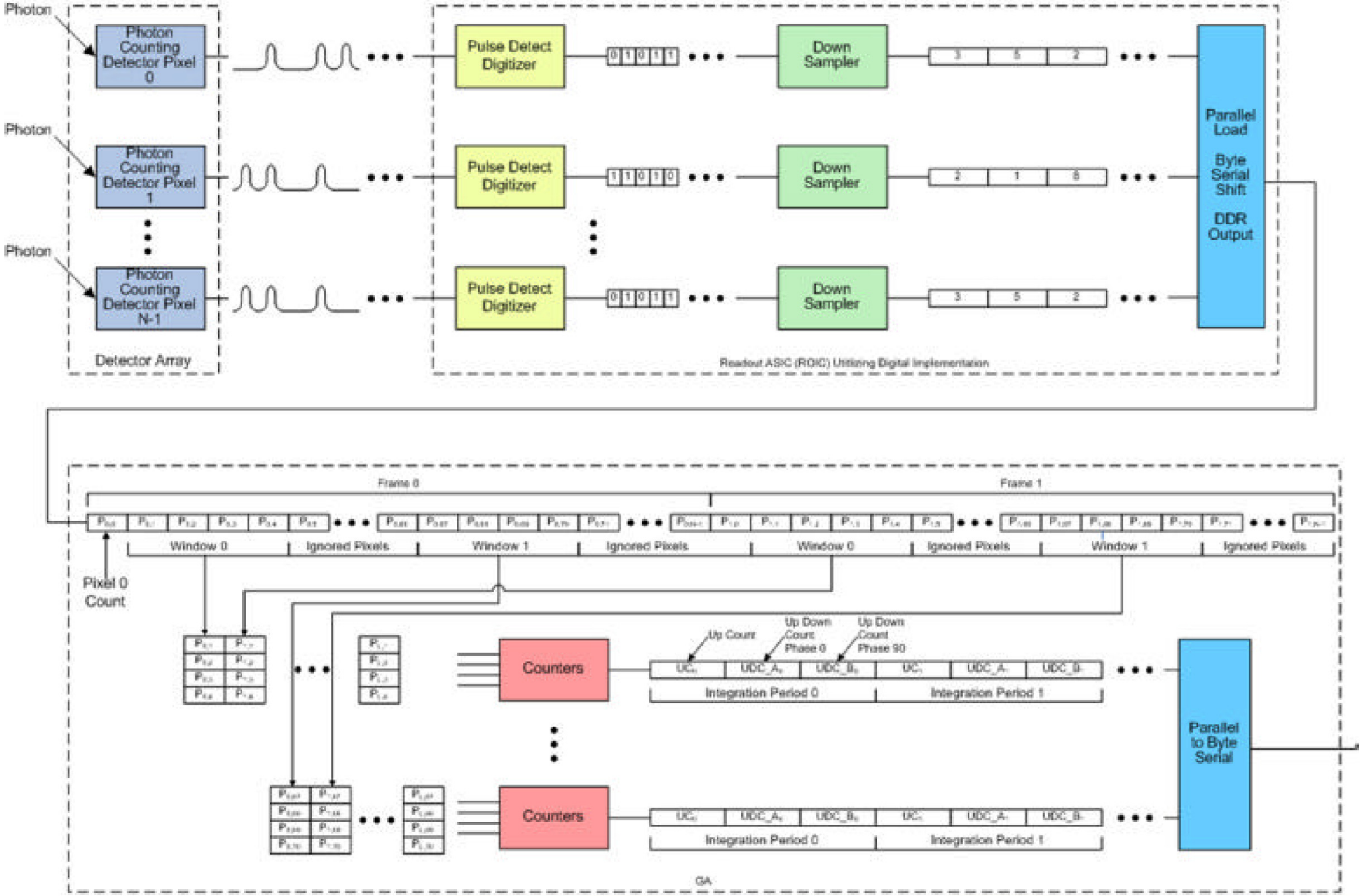
Array Read-Out Integrated Circuit

- **Parallel processing of all the pixels exceeds the resources available in current application-specific integrated circuit (ASIC) and gate array (GA) technology**
  - Desire for a high fill factor in the detector array also precludes this
- **Processing can be distributed across an ASIC and GA through down-sampling and windowing portions of the detector array**



Down-sampling with Windowing

- **Down-sampling:** Photon counters read out and cleared at a fixed interval
- **Windowing:** Samples are decimated at gate array input



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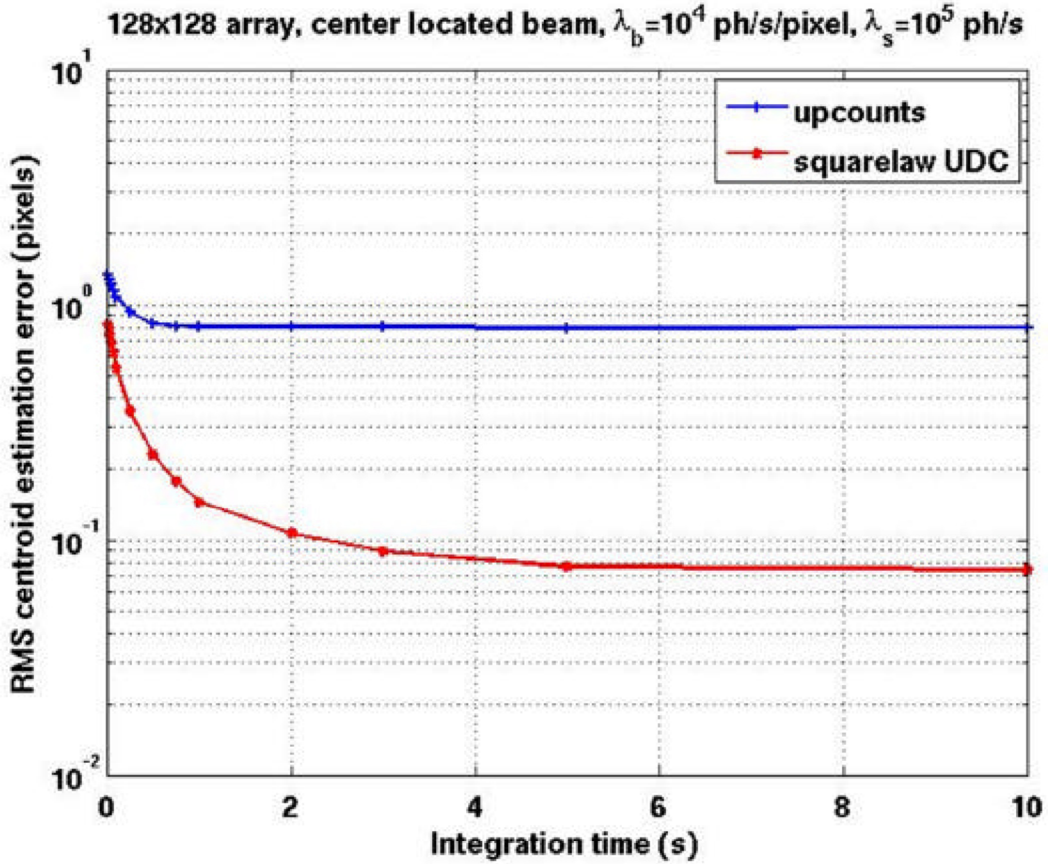
Current Status

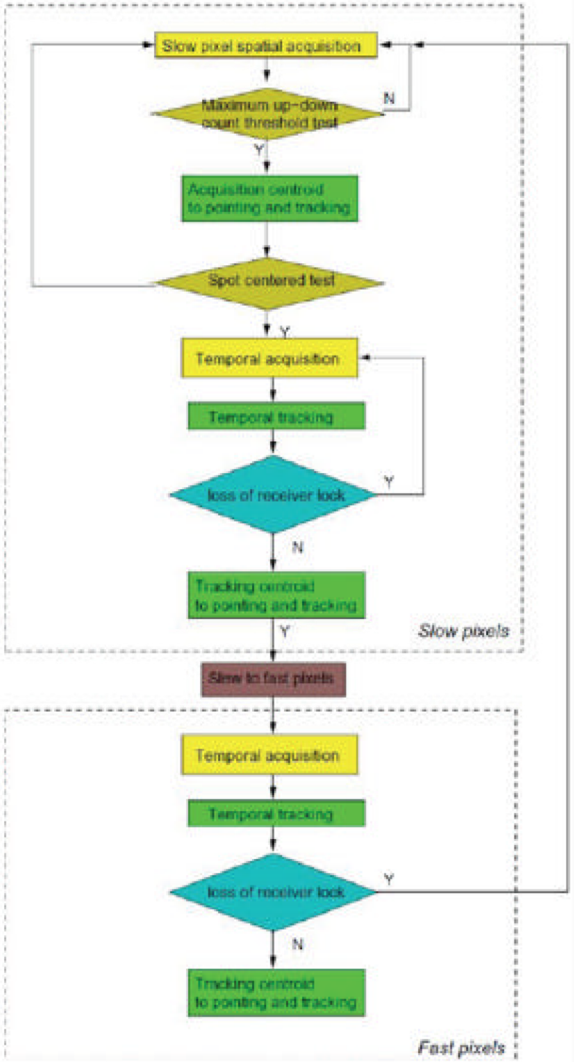
- **Expected performance gains have been confirmed by simulation models**
  - Simulation inputs are measured spacecraft vibration data and measured small array (4x4 and 6x6) detector performance data
- **ASIC functionality is presently being prototyped using field-programmable gate array**
  - For a 32-pixel "proof-of-concept" demonstration prior to fabrication of a ROIC for bump-bonding to 32x32 pixel arrays
- **An emulation test-bed has been set up to confirm simulation predictions using incoming photon counting detector arrays**
  - Shot noise limited tracking performance has been confirmed using a 6x6 GM-APD array
  - 32x32 arrays in RCE Si GM-APD, InGaAsP GM-APD, and InGaAs and InGaAsP NAF technologies will be tested over next 12-18 months

Simulated Tracking Performance

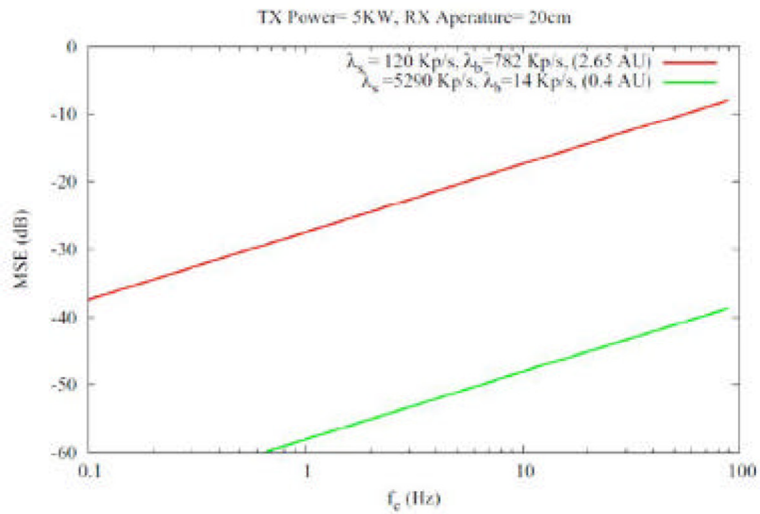
- **Use of the square-law up-down counter (UDC) statistic improves centroiding performance of the uplink beam over conventional energy detection using up-counters**



Beacon Acquisition



- **Temporal acquisition of the uplink beacon square wave signal uses outputs from the pair of phase-offset counters**
- **Once a signal is detected on the slow pixels, the transceiver is pointed to place the uplink on the fast pixels**



Summary

- **Use of SPD arrays with per-pixel counters instead of traditional analog detector arrays allows acquisition and tracking performance at the theoretical limit for precision optical beam pointing**
  - *Required laser beacon power for acquisition and tracking can be reduced by a factor of 10 to 100, thus motivating detector technology development*
  - *SPD array pixels can have sub-nanosecond timing resolution, allowing for uplink data recovery or range measurements*
- **Although continued detector array development is still needed, the primary "missing piece" is the application specific read-out integrated circuit**
  - *Required post-detector functionality can be met by a down-sampling read-out ASIC followed by a post-processing gate array*

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