Deep Space Acquisition and Tracking with Single Photon Detector Arrays

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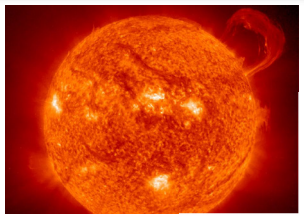
Jet Propulsion Laboratory • California Institute of Technology

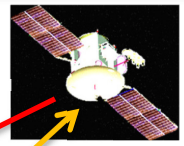
Deep Space Optical Communications



Sun

Can be field of view

Primary source of optical noise



Deep Space

Large distance

Large $1/R^2$ range loss

Large 2R/c round-trip light time

Point-Ahead Angle

Downlink

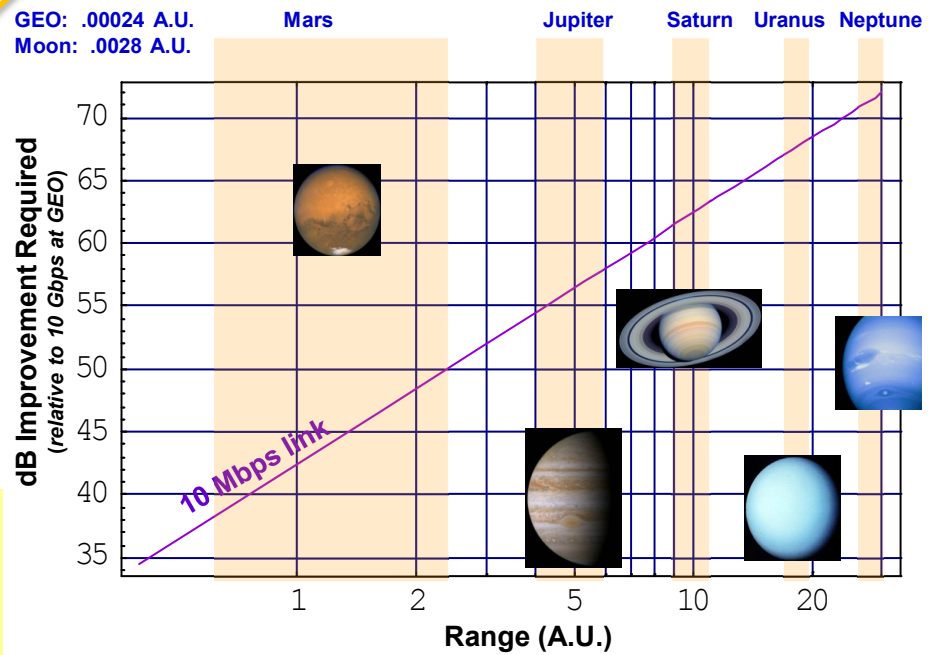
- Stabilized by vibration isolation system & uplink beacon
- Gb/s return link data
- Ranging

Earth at T_1+RTLT

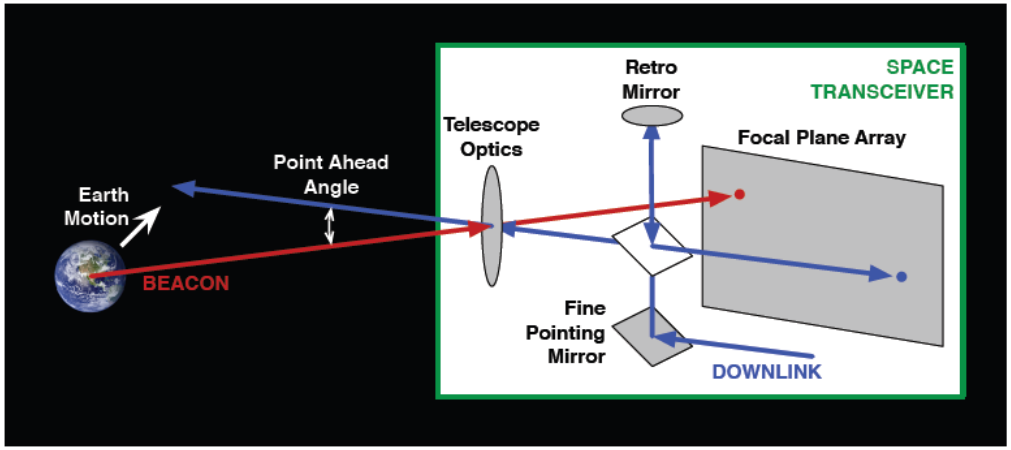
Earth at T_1

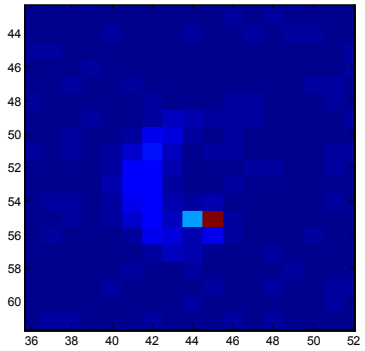
Uplink

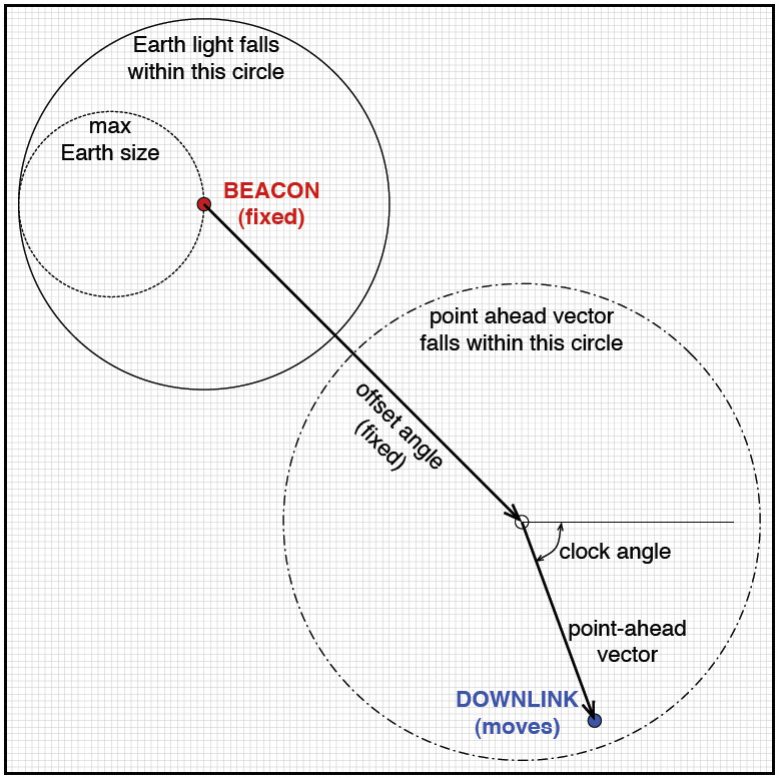
- Blind points to spacecraft
- Aids downlink pointing
  - *Reference for removal of S/C jitter*
  - *Reference for point-ahead angle*
- Mb/s forward link data
- Ranging



Transceiver Beam Relationships

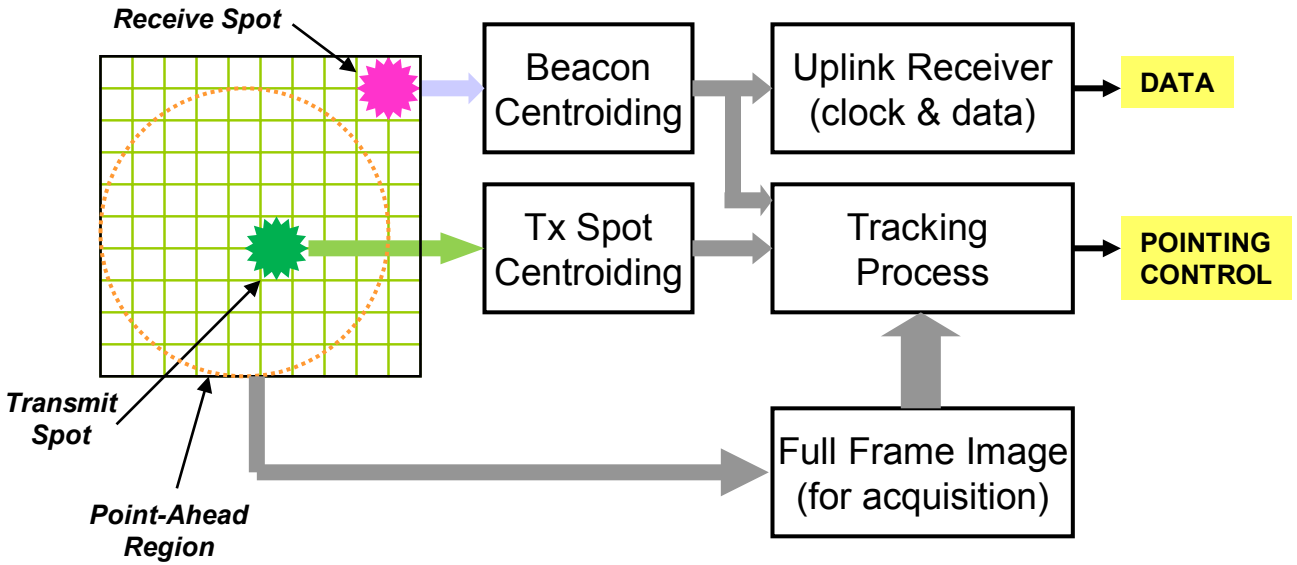




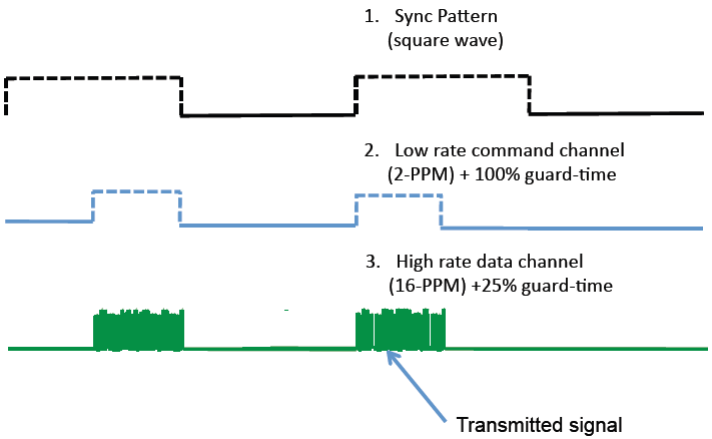


- **Must form an accurate estimate of the location of the dim laser beacon to point the transmit beam to the Earth receiver location**
- **The point ahead angle depends on the transverse component of the Earth's velocity relative to the spacecraft**
  - In deep space applications with light propagation times of many minutes the point ahead angle can be many beam widths
- **Handshaking with the Earth receiver to confirm point ahead in real time is not possible**
  - A local relative measurement must be made

Acquisition, Tracking, and Data Detector

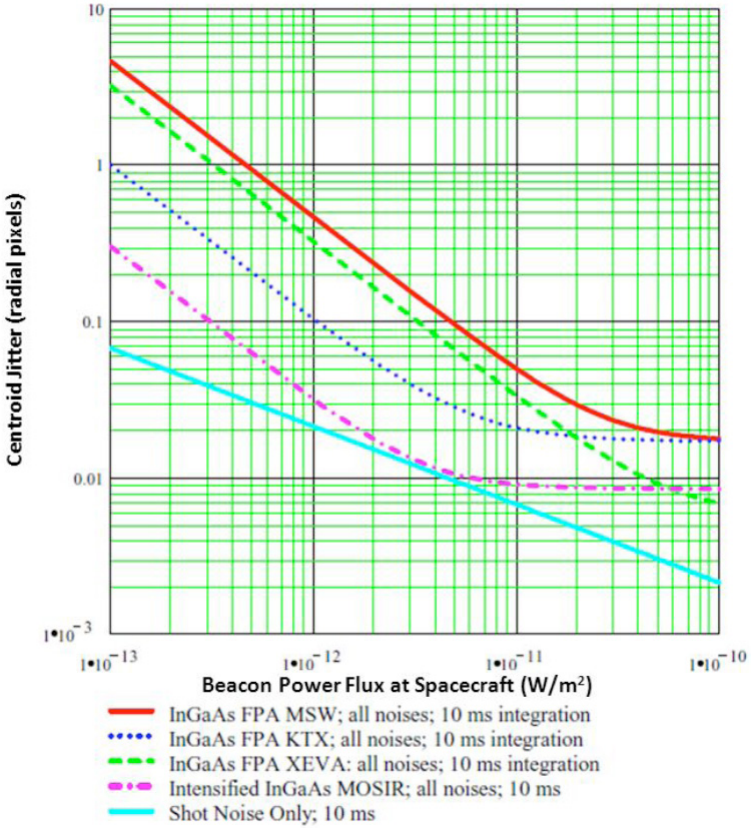


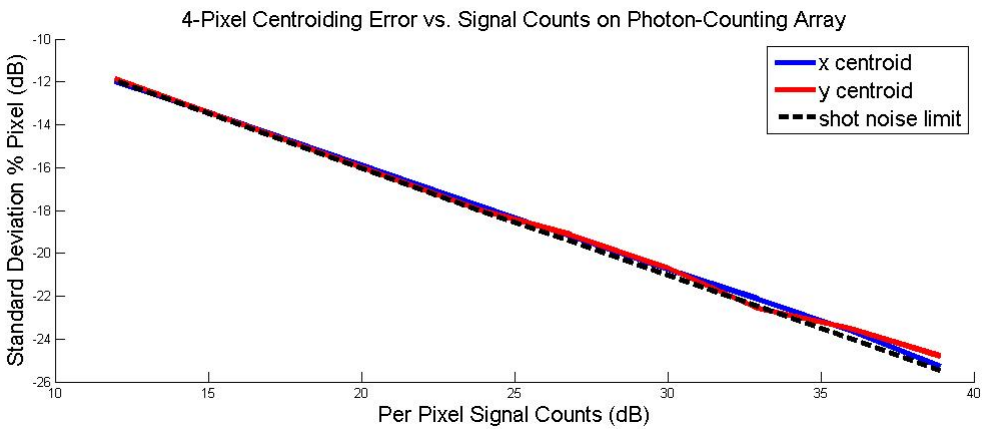
- **Single focal plane receiver architecture with simultaneous acquisition, tracking and uplink data demodulation**
  - Versus two or three typical for an optical receiver design
  - Reduces transceiver mass – Increases transceiver reliability
- **A nested beacon modulation scheme can be used for background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

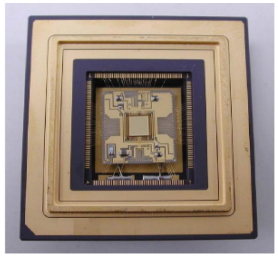


Analog vs. Photon Counting

- **A significant limitation on 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

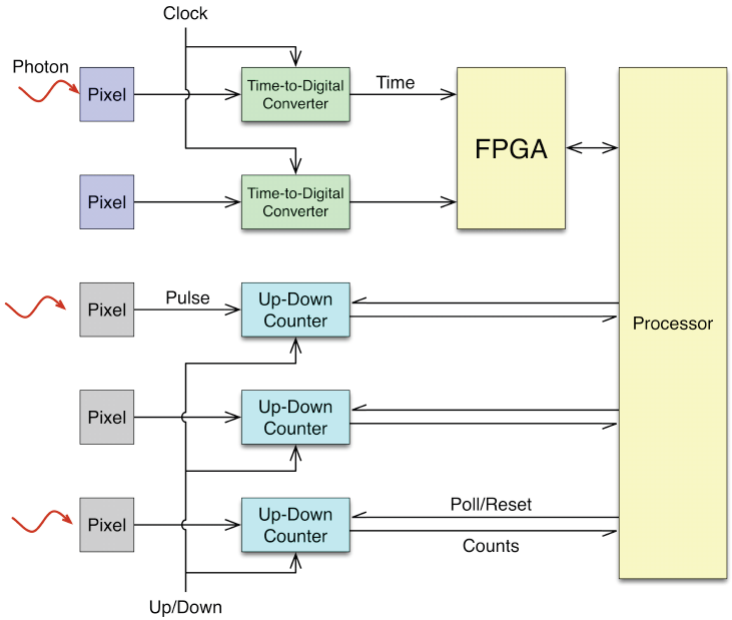


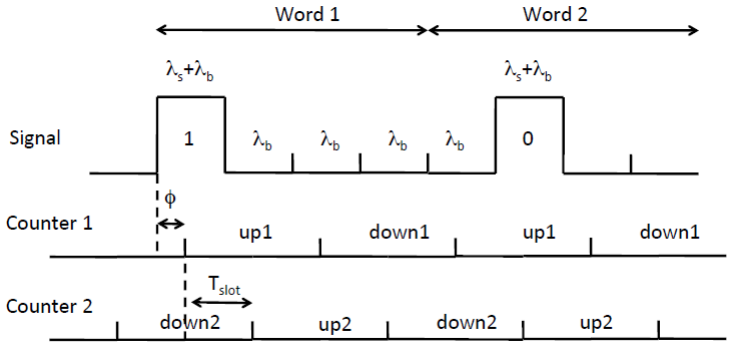




32x32 SPD array

Pixel Processing



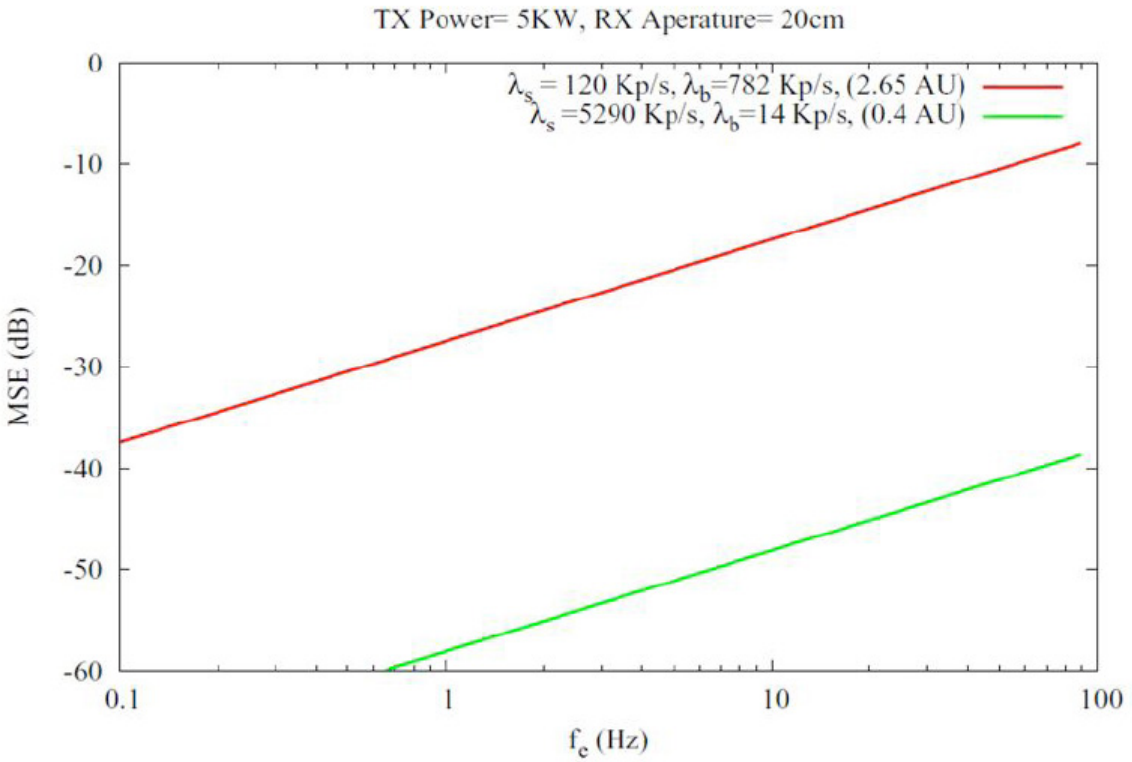


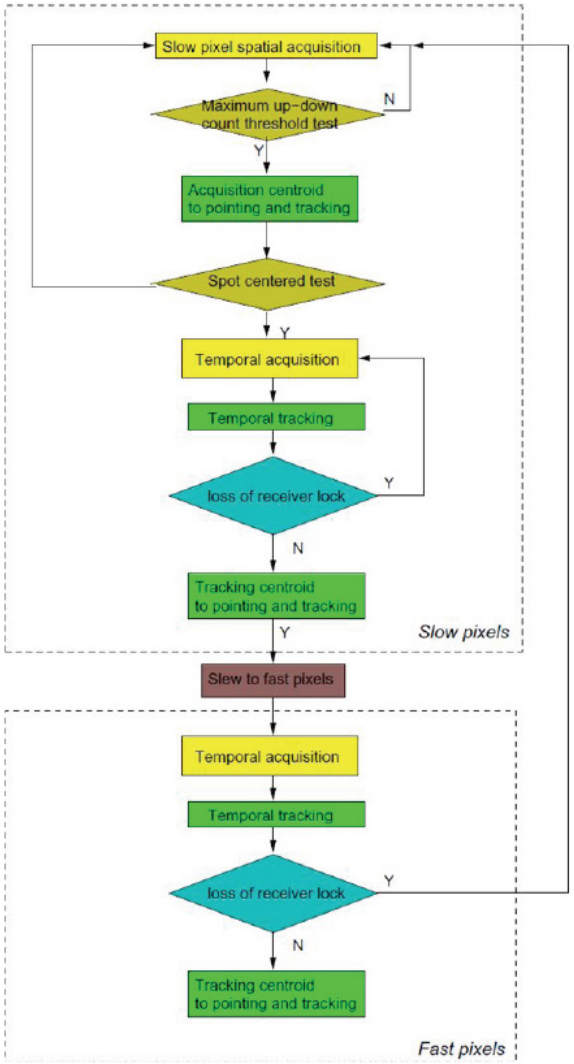
- **The focal plane array is composed of "slow" and "fast" pixels**
  - A 2x2 or larger sub-array of fast pixels is located at the beacon tracking position
- **When the "slow" counters are alternating between the "up" and "down" modes, the background rate has no average effect on the counter state**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

$$\left.\begin{aligned} \langle up \rangle &= 4\lambda_b T_{slot} - \lambda_s \phi + 2\lambda_s T_{slot} \\ \langle down \rangle &= 4\lambda_b T_{slot} + \lambda_s \phi \\ \langle up \rangle - \langle down \rangle &= 2\lambda_s T_{slot} - 2\lambda_s \phi \\ \langle up \rangle + \langle down \rangle &= 8\lambda_b T_{slot} + 2\lambda_s \phi \end{aligned}\right\} \text{Counter 1}$$

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

Acquisition and Tracking





- **Temporal acquisition of the uplink beacon square wave signal uses outputs from a pair of phase-offset counters**
  - Combining the two counters yields an estimate of the incident signal level, while allowing the pulses from noise and background radiation to cancel out
- **Once a signal is detected on the slow pixels, the transceiver can be pointed to place the uplink on the fast pixels**

Summary

- **Use of SPD arrays with per-pixel counters allows centroiding 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*
- **SPD array pixels can have sub-nanosecond timing resolution, allowing precision recovery of photon time-of-arrival information**
  - *For uplink data recovery or range measurements*

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