Deep Space Acquisition and Tracking with Single Photon Detector Arrays

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Deep Space Optical Communications

Sun
Can be field of view
Primary source of optical noise

Deep Space
Large distance
Large 1/R² range loss
Large 2R/c round-trip light time

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

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

Earth at T₁+RTLT
Earth at T₁
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

Beacon Centroiding

Uplink Receiver (clock & data)

Tracking Process

Full Frame Image (for acquisition)

1. Sync Pattern (square wave)
2. Low rate command channel (2-PPM) + 100% guard-time
3. High rate data channel (16-PPM) + 25% guard-time

Transmitted signal
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 with 10 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
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

\[
\begin{align*}
\langle up \rangle &= 4\lambda_b T_{slot} - 3\lambda_s \phi + 2\lambda_s T_{slot} \\
\langle down \rangle &= 4\lambda_b T_{slot} + 3\lambda_s \phi \\
\langle up \rangle - \langle down \rangle &= 2\lambda_b T_{slot} - 2\lambda_s \phi \\
\langle up \rangle + \langle down \rangle &= 8\lambda_b T_{slot} + 2\lambda_s \phi
\end{align*}
\]
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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