Photon Counting Detector Array Algorithms for Deep Space Optical Communications

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ABSTRACT

For deep-space optical communications systems utilizing an uplink optical beacon, a single-photon-counting detector array on the flight terminal can be used to simultaneously perform uplink tracking and communications as well as accurate downlink pointing at photon-starved (pW/m²) power levels. In this paper, we discuss concepts and algorithms for uplink signal acquisition, tracking, and parameter estimation using a photon-counting camera. Statistical models of detector output data and signal processing algorithms are presented, incorporating realistic effects such as Earth background and detector/readout blocking. Analysis and simulation results are validated against measured laboratory data using state-of-the-art commercial photon-counting detector arrays, demonstrating sub-microradian tracking errors under channel conditions representative of deep space optical links.

Keywords: Optical communications, photon counting, beacon tracking

1. INTRODUCTION

Optical communication technology offers the promise of data rates that are significantly higher than those provided by conventional radio-frequency-based technology. For deep-space applications, power efficient communications is possible in part due to the large effective power gain from narrow optical beamwidths. Consequently, a necessary component of optical communication systems is highly accurate and stable laser beam pointing.

In order to establish and maintain an optical link, accurate uplink and downlink pointing must be performed in the presence of spacecraft motion and disturbances. Disturbance suppression can be achieved through a combination of passive isolation to reduce mechanical coupling between the spacecraft and flight terminal platform, and active cancellation of pointing errors through platform steering and downlink beam steering via a fine steering mirror. Local reference sensors such as inertial reference units may be utilized to provide highly accurate information for active disturbance cancellation, but increase mass and power on the flight terminal, and do not provide a pointing reference to the Earth. In order to minimize mass on the spacecraft transceiver, the Deep Space Optical Communication (DSOC) project at the Jet Propulsion Laboratory uses an uplink beacon transmitted from the ground terminal to provide a reference spot position that may be tracked by the flight terminal. By estimating the uplink signal position, the flight terminal platform attitude may be adjusted and the point-ahead angle for downlink transmission may be calculated and implemented. Furthermore, an uplink beacon can also carry command and configuration data. By using a single photodetector array for both pointing and communications, rather than a more conventional architecture consisting of separate detectors for tracking and communications, beam alignment errors and optical losses as well as overall system complexity may be minimized. A photon counting array possesses the best combination of sensitivity and bandwidth for these purposes. Signal processing algorithms for uplink spatial acquisition and tracking, parameter estimation, and command telemetry processing must therefore be developed in order to simultaneously support tracking and communications for the deep-space optical link.

In this paper, we evaluate signal processing algorithms for uplink spatial acquisition, tracking and parameter estimation based upon use of a single photon counting detector array. We discuss the uplink beacon signal

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format and detector array modeling. Algorithms for background subtraction and parameter estimation, signal
detection, and centroiding are presented, followed by performance results obtained through computer simulation
and laboratory testing with a commercial photon counting camera. The results show that these algorithms can
achieve high probability of signal detection and accurate uplink tracking with very low received beacon power
and severe background levels typical of deep space optical link conditions.

2. SYSTEM OVERVIEW AND MODELING

Figure 1. Deep space optical communications flight terminal pointing and tracking concept

The deep-space optical communications flight transceiver\(^1\) relies upon use of a modulated uplink beacon
in order to assist downlink pointing and provide uplink command and data links. As shown in Figure 1, a
single aperture for both transmit and receive beams simplifies boresight alignment issues and enables continuous
monitoring of the downlink point-ahead angle by imaging both uplink and downlink signals onto one common
focal plane array (FPA) of single-photon-counting detectors, which is used for uplink acquisition and tracking,
downlink point-ahead verification, and uplink data detection. The FPA converts the uplink photons into attitude
information based upon the spatial distribution of photons on the detector pixels, and into temporal information
via time of arrival data that is used to recover the pulse-position modulated uplink data. The major FPA signal
processing operations are

- **Uplink beacon detection and acquisition**: Scanning of the flight transceiver platform to detect and
coarsely determine the uplink beacon position.

- **Uplink beacon tracking**: Fine estimation and control of the uplink beacon position.

- **Downlink point-ahead verification**: Position estimation of the retro-reflected portion of the downlink
laser to verify the angular offset between the received beacon and the downlink transmitted beam.

- **Uplink data demodulation**: Timing synchronization, parameter estimation, and data decoding.

2.1 Uplink Beacon Signal

The uplink signal is a nested modulation format that contains a low-bandwidth command channel and an optional
higher rate data channel. The inner data modulation consists of higher order pulse position modulation (PPM),
while the low rate outer command modulation consists of 2-PPM with two intersymbol guard-time (ISGT) slots\(^2\)
(see Figure 2). If the optional high rate data channel is included, a block of higher order PPM symbols (with
ISGT) is sent in one of two time intervals of duration \(T_c\), which are followed by two additional time intervals of
duration \(T_c\) with no signal, thereby creating the 2-PPM + 2-ISGT command symbol of duration \(4T_c\). If the high
rate data is not included, then the 2-PPM + 2-ISGT with slot duration \(T_c\) is implemented directly. In either
case, the average intensity envelope of the combined modulation layers is a square wave that forms a beacon
signal whose alternating pattern may be exploited for background rejection,\(^3\) signal acquisition and tracking.
Here we shall assume that the higher rate data channel is not implemented.
1. Beacon Sync Pattern
(square wave)

2. Low rate command channel
(PPM 2 and 2 guard slots)

3. High rate data channel
(PPM 8 and 4 guard slots)

Figure 2. Uplink nested modulation signal structure

2.2 Detector Output
The flight detector consists of a square array of Geiger mode avalanche photodiode (APD) detectors. Each detector pixel in the array is a single-photon-counting detector that outputs an electrical pulse in response to a photon arrival. When operating in Geiger mode, the APD must be quenched after each photon event and then held disarmed for a recovery period, introducing a dead time into the detection process. The result is that photons arriving after the initial photon arrival and before the end of the dead time interval cannot be detected. This blocking effect limits the output count rate of the detector and reduces the effective detection efficiency. The recovery time, or dead time, is typically an adjustable quantity. The output count rate is also limited by the readout frame rate; the readout integrated circuit (ROIC) bonded to the APD array outputs a timestamp corresponding to each detected photon arrival pulse, and this timestamp output is gated so that at most one timestamp per pixel is produced for each readout frame interval of duration $T_f$. Consequently, for each pixel, only the first photon arrival detected in any frame interval gives rise to an output timestamp, or count. The flight detector blocking model is illustrated in Fig. 3, where some incident photon arrivals are undetected due to the APD dead time $\tau$, and others go undetected due to the ROIC frame limit. In our application, the APD dead time $\tau$ is on the same order as the frame time $T_f$, so in order to simplify analysis we combine the two effects into a single non-paralyzable blocking model with blocking time $\tau$.

For the signal processing functions listed in Section 2, it is sufficient to know the number of photon counts over various time intervals rather than the high resolution timestamp values. In the absence of detector blocking time, the number of detected photon events is modeled as a Poisson process in which the probability of detecting $k$ events over a time interval of duration $T$ is given by

$$P[X(T) = k] = \frac{(\lambda T)^k}{k!} e^{-\lambda T}$$  \hspace{1cm} (1)

where $X(T)$ is the number of detected counts over an interval of duration $T$ and $\lambda$ is the average photon arrival rate. Once blocking is considered, the blocked detected count process $X_{bl}(T)$ is no longer Poisson, but may be approximated as Gaussian distributed with mean and variance

$$E[X_{bl}(T)] \approx \frac{\lambda T}{1 + \lambda \tau}, \hspace{0.5cm} Var[X_{bl}(T)] \approx \frac{\lambda T}{(1 + \lambda \tau)^2}, \hspace{0.5cm} \text{for } \tau < T.$$  \hspace{1cm} (2)

Figure 4 shows histograms of slot count statistics collected from simulations of the detector output for a case with mean signal counts per symbol $K_s \triangleq \lambda_s T_{sym} = 7$ and mean background counts per slot of $K_b \triangleq \lambda_b T_{slot} = 16$. The probability mass functions of the unblocked Poisson count processes for the signal and non-signal slots are shown, along with corresponding histograms for the simulated blocked process with $\tau/T_{slot} = 0.03$. The Gaussian model for the blocked probability mass function is also plotted, demonstrating that it is a good approximation to the simulated process. We observe that the effect of blocking is to reduce the mean of the signal slot (which
contains signal plus background) from 23 to 13, and that of the background-only slot from 16 to 11. The variance of the blocked probability mass functions are also reduced. As the number of incident background photons increases to the point at which the detector is saturated (a count always detected in every ROIC output frame), the blocked signal and background slot count distributions move closer together and further to the right, both eventually reaching the value $T_{\text{slot}}/\tau$, resulting in losses in spatial tracking and data demodulation.

Figure 3. Detector/readout pixel blocking

Figure 4. Unblocked and blocked photoelectron count statistics for signal and background slots, showing histograms from blocking simulation and Gaussian blocked count model
3. ALGORITHMS

We focus upon algorithms for spatial signal detection and tracking using the beacon sync pattern, as well as signal parameter estimation. Signal processing for the demodulation and decoding of the transmitted uplink data is not addressed in this paper. For spatial tracking, the objective is to estimate the position of the uplink beacon spot upon the FPA in order to provide an accurate reference for pointing the downlink beam. This position estimate must have sub-microradian accuracy. In the presence of high background fluxes, the accuracy of the position estimate is compromised. For example, the traditional centroid algorithm, which in the limit is the maximum likelihood position estimate, will produce an estimate that is biased towards the center of mass of the Earth. In order to obtain an unbiased position estimate, our approach is to perform the centroiding on a set of statistics that have been modified to effectively subtract out the contribution from background photons. By alternately incrementing and decrementing two photon arrival counters (“up-down counting”) that are offset by one-quarter of the square wave period,\(^3,8\) we can construct pixel statistics for detecting signal presence in the absence of temporal synchronization of the counters with the received signal. This leads to a faster spatial acquisition and tracking sequence.

3.1 Background Subtraction

The average transmitted slot intensity is shown in Figure 5 for the 2-PPM signal with 2 ISGT slots. The flight detector array readout frames are clocked at a multiple of the transmitted slot rate, so that the flight electronics receive multiple samples per transmitted slot. Assume that there is a timing offset of \(\delta T_{\text{slot}} = (k + \epsilon)T_{\text{slot}}\) between the transmitted and receiver symbol clocks, where \(k \in \{0, 1, 2, 3\}\) and \(0 \leq \epsilon < 1\), and that the clocks have no significant frequency offset or drift over the duration that an estimate is made. For any given pixel, the sampled version of the received signal consists of slot counts obtained by summing the number of valid timestamps corresponding to detected photoelectron counts over each slot duration. These counts are then alternately added and subtracted at twice the symbol frequency over \(N\) 2-PPM+2-ISGT symbols to form “up-down” counter statistics. We can equivalently analyze this process by first accumulating the counts over \(N\) 2-PPM+2-ISGT symbols into one of four slot count bins denoted by the statistics \(X_0, X_1, X_2, \) and \(X_3\). More explicitly, if \(\{x(n)\}\) is the series of slot counts, then

\[
X_m = \sum_{n=0}^{N-1} x(4n + m), \quad m \in \{0, 1, 2, 3\},
\]

(3)
In the absence of blocking, assuming that $k = 0$, the means and variances of the accumulated slot statistics are

$$E[X_0] = Var[X_0] = N\lambda_s T_{\text{slot}} + 2N\lambda_s T_{\text{slot}}$$  \hspace{1cm} (4)$$
$$E[X_1] = Var[X_1] = N\lambda_s T_{\text{slot}} + 2N(1 - \epsilon)\lambda_s T_{\text{slot}}$$  \hspace{1cm} (5)$$
$$E[X_2] = Var[X_2] = N\lambda_s T_{\text{slot}}$$  \hspace{1cm} (6)$$
$$E[X_3] = Var[X_3] = N\lambda_s T_{\text{slot}} + 2N\epsilon\lambda_s T_{\text{slot}},$$  \hspace{1cm} (7)$$

The two up-down counter statistics $U$ and $V$, offset in quadrature, are then calculated for each detector pixel as

$$U = X_0 + X_1 - X_2 - X_3$$  \hspace{1cm} (8)$$

and

$$V = X_0 - X_1 - X_2 + X_3.$$  \hspace{1cm} (9)$$

Additionally, an up-counter that simply accumulates all of the counts over $N$ symbols is formed for each pixel, and is denoted by

$$S = X_0 + X_1 + X_2 + X_3.$$  \hspace{1cm} (10)$$

For general values of the integer part $k$ of the symbol offset, the expected values of the counter outputs are given by

$$E[U] \equiv \mu_1(k, \epsilon, \lambda_s) = \begin{cases} 4N(1 - \epsilon)\lambda_s T_{\text{slot}} & k = 0 \\ -4N\epsilon\lambda_s T_{\text{slot}} & k = 1 \\ -4N(1 - \epsilon)\lambda_s T_{\text{slot}} & k = 2 \\ 4N\epsilon\lambda_s T_{\text{slot}} & k = 3 \end{cases}$$  \hspace{1cm} (11)$$

$$E[V] \equiv \mu_2(k, \epsilon, \lambda_s) = \begin{cases} 4N\epsilon\lambda_s T_{\text{slot}} & k = 0 \\ 4N(1 - \epsilon)\lambda_s T_{\text{slot}} & k = 1 \\ -4N\epsilon\lambda_s T_{\text{slot}} & k = 2 \\ -4N(1 - \epsilon)\lambda_s T_{\text{slot}} & k = 3 \end{cases}$$  \hspace{1cm} (12)$$

and

$$E[S] = 4N(\lambda_b + \lambda_s)T_{\text{slot}} \quad \forall k.$$  \hspace{1cm} (13)$$

In the absence of blocking, the variances of these random variable are all equal to each other, and given by

$$\text{Var}[U] = \text{Var}[V] = \text{Var}[S] = 4N(\lambda_b + \lambda_s)T_{\text{slot}} \equiv \sigma^2$$  \hspace{1cm} (14)$$

We observe from (11) and (12) that the expected values of the two up-down counters $U$ and $V$ are functions of the the signal flux $\lambda_s$ but not the background flux $\lambda_b$, and may therefore be used to estimate the position of the signal while the effect of background is mitigated. For ease of analysis, we approximate the distribution of $U, V, S$ to be Gaussian with the means and variances given above, which is a reasonable assumption for the integration times involved. We add the indices $(i, j)$ to the counter notation to denote the pixel statistic from the $i$-th column and $j$-th row of the detector array. It may be shown that conditioned upon the values $k, \epsilon, \lambda_{s,i,j}$, and $\lambda_{b,i,j}$,

$$\text{Cov}[U_{i,j}, V_{i,j} | k, \epsilon, \lambda_{s,i,j}, \lambda_{b,i,j}] = 0, \quad \forall i, j.$$  \hspace{1cm} (15)$$

Here, $\lambda_{s,i,j}$ and $\lambda_{b,i,j}$ are the mean signal and background fluxes for pixel $(i, j)$. We also assume for analytical purposes that

$$\text{Cov}[U_{i,j}, U_{l,m} | k, \epsilon, \{\lambda_s\}, \{\lambda_b\}] = \text{Cov}[V_{i,j}, V_{l,m} | k, \epsilon, \{\lambda_s\}, \{\lambda_b\}] = \text{Cov}[S_{i,j}, S_{l,m} | k, \epsilon, \{\lambda_s\}, \{\lambda_b\}] = 0,$$

$$\forall (i, j) \neq (l, m).$$  \hspace{1cm} (16)$$

This last assumption in (16) does not generally hold for real detectors – in practice there is measurable crosstalk between pixels leading to non-zero covariance. Also note that $\text{Cov}[U_{i,j}, S_{i,j}]$ and $\text{Cov}[V_{i,j}, S_{i,j}]$ are nonzero.
3.2 Signal Detection and Acquisition

The joint probability density function of the statistics $U_{i,j}$, $V_{i,j}$, and $S_{i,j}$ may be formed using the Gaussian approximations and means and variances given in Section 3.1, and the sufficient statistic for signal detection and parameter estimation may then be derived. As this is mathematically intensive, we use heuristic decision statistics obtained from inspection of the expressions in Section 3.1. The statistic $U^2_{i,j} + V^2_{i,j}$ makes intuitive sense given the quadrature nature of the offset up-down counters and the similarities with non-coherent radio frequency carrier envelope detection. However, it may be shown that the expected value of this square-law statistic depends upon the background flux, which would result in a bias in the estimation of the beacon position in the presence of nonuniform background, as well as degradation in signal detection performance. We remove this bias by subtracting twice the up-count output of each pixel from the square-law statistic, leading to the modified square-law statistic

$$W_{i,j} = U^2_{i,j} + V^2_{i,j} - 2S_{i,j}$$

with mean

$$E[W_{i,j} | \epsilon, \lambda_{s_{i,j}}, \lambda_{b_{i,j}}] = \lambda^2_{s_{i,j}} T^2_{\text{int}}(1 - 2\epsilon + 2\epsilon^2).$$

The variance is more complicated; however, averaging over the fractional timing offset $\epsilon$, we obtain

$$E[Var[W(i,j)]] = \frac{8}{3} \lambda_s(i,j)^2 T^4_{\text{int}} + \frac{8}{3} \lambda_b(i,j) \lambda_s(i,j)^2 T^3_{\text{int}} + \frac{8}{3} \lambda_s(i,j)^3 T^3_{\text{int}} - \frac{4}{3} \lambda_s(i,j)^2 T^2_{\text{int}} + 4 \lambda_b(i,j)^2 T^2_{\text{int}} + 8 \lambda_b(i,j) \lambda_s(i,j) T^2_{\text{int}} + 4(\lambda_b(i,j) + \lambda_s(i,j)) T_{\text{int}},$$

which is a function of higher order powers of the signal as well as background, due to the squaring operation. Note that this leads to more noise in the estimates obtained using the modified square-law statistic when compared with use of the simple up-counts, but less background-induced bias.

In order to detect the presence of the beacon signal, we sum the modified square-law statistics $W_{i,j}$ over a subwindow with $LxL$ pixels. This sum of modified square-law statistics $Z = \sum_{i=0}^{L-1} \sum_{j=0}^{L-1} W_{i,j}$ can be approximated as Gaussian with mean $\eta$ and variance $\rho$. The probability distribution function of the subwindow statistic $Z$ is

$$P(Z < z) = \Phi \left( \frac{z - \eta}{\sqrt{\rho}} \right).$$

In order to design a detection threshold to determine whether or not the signal is in a particular subwindow indexed by $k$, we compare $Z_k$ with a threshold $\gamma_k$. The false alarm probability is then the probability that $Z_k$ exceeds $\gamma_k$ under the null hypothesis $H_0$ (signal absent). If we specify that the false alarm probability should not exceed some level $\alpha$, i.e.,

$$P_{fa} = P[Z_k > \gamma | H_0] < \alpha,$$

we find that the decision threshold is given by

$$\gamma = E[Z_k | H_0] - \sqrt{Var[Z_k | H_0]} \Phi^{-1}(P_{fa}).$$

Under the null hypothesis $H_0$,

$$E[Z_k | H_0] = 0$$

and

$$Var[Z_k | H_0] = \sum_{i=0}^{L-1} \sum_{j=0}^{L-1} Var[W_{i,j}] = 4T^2_{\text{int}} \sum_{i=0}^{L-1} \sum_{j=0}^{L-1} \lambda^2_{b_{i,j}} + 4T^2_{\text{int}} \sum_{i=0}^{L-1} \sum_{j=0}^{L-1} \lambda_{b_{i,j}}.$$  

For large background count levels, the first term dominates, and the signal detection threshold for false alarm probability $\alpha$ is

$$\gamma = 2T_{\text{int}} \sqrt{\sum_{i=0}^{L-1} \sum_{j=0}^{L-1} \lambda^2_{b_{i,j}} Q^{-1}(\alpha)},$$

where $Q^{-1}(\alpha)$ is the inverse of the complementary error function.

Proc. of SPIE Vol. 9739 97390X-7
where $Q(x) = 1 - \Phi(x)$. The probability of missed detection with this threshold is then given by

$$P_{md} = P[Z_k < \gamma | H_1],$$

(23)

where $H_1$ is the signal present hypothesis. Note that in practice the probabilities of false alarm and missed detection may diverge significantly from the value of $\alpha$ used in designing the threshold and from the corresponding analytical expression for the probability of missed detection. This is due in part to the fact that the two-dimensional uplink signal intensity can spread out over multiple pixels and across subwindow boundaries, so detecting its presence in a subwindow is not a purely binary hypothesis problem.

During uplink beacon detection and acquisition, the spacecraft pointing uncertainty region is scanned to detect the signal. Using an estimate of the background obtained beforehand to compute the threshold, the signal detection statistic $Z_k$ is calculated for all of the subwindows of the array. The size and number of subwindows may be adjusted based upon the background level, required performance, and flight electronics processing capability. A simple alternative algorithm consists of calculating the modified square-law statistic for each individual pixel, finding the maximum, and comparing that value to the threshold $\gamma$ calculated for a single pixel.

### 3.3 Centroiding

In order to estimate the location of the uplink signal for the purpose of pointing and tracking, a centroid estimate is used in which the weight used for each pixel may be either the up-count statistic $S_{i,j}(k)$ or the modified square-law up-down counter statistic $W_{i,j}(k)$, where the indices $i$, $j$, and $k$, indicate the pixel in the $i^{th}$ row and $j^{th}$ column of the particular subwindow $k$. The uplink centroid estimate $\hat{C}(k) = (\hat{x}(k), \hat{y}(k))$, using the modified square-law up-down counter statistic, is calculated as

$$\hat{x}(k) = \frac{\sum_{j=0}^{N_{col}-1} (j + 0.5) \sum_{i=0}^{N_{rows}-1} W_{i,j}(k)}{\sum_{j=0}^{N_{col}-1} \sum_{i=0}^{N_{rows}-1} W_{i,j}(k)}$$

$$\hat{y}(k) = \frac{\sum_{i=0}^{N_{col}-1} (i + 0.5) \sum_{j=0}^{N_{rows}-1} W_{i,j}(k)}{\sum_{j=0}^{N_{col}-1} \sum_{i=0}^{N_{rows}-1} W_{i,j}(k)}$$

(24)

where $N_{col}$ and $N_{rows}$ are the number of columns and rows in the subwindow, and $\hat{x}$ and $\hat{y}$ are given in pixel units. The conventional centroid estimate using the up-counts may be obtained by substituting the statistics $S_{i,j}(k)$ for $W_{i,j}(k)$ in (24). The performance of the centroid estimate may be evaluated via simulation and quantified as centroiding bias and jitter (RMS error).

Once the uplink beacon has been detected, the centroid formula in (24) is calculated over a specified size subwindow in order to steer the platform to move the beacon to the pixel crosshairs of a designated tracking region. At that point, the subwindow size is reduced to eliminate background, and the beacon centroid estimate is used to maintain the uplink beam position so that temporal synchronization and data demodulation may commence. The downlink transmitter may then be turned on and pointed using the uplink beacon reference position and ephemeris data provided by the spacecraft. The downlink pointing is confirmed by splitting off a portion of the transmitted beam power to be retro-reflected onto the detector array so that its position may also be estimated. As the downlink modulation occurs at a much higher rate than may be processed by the flight detector readout electronics, up-down counting background subtraction cannot be used for downlink detection. Instead, the conventional centroid estimate using the up-counts is used to estimate and track the downlink spot position. As the downlink signal is expected to be in a location of the detector array separated from the uplink beacon and the Earth, we do not expect in-band background to interfere as much with its tracking. Furthermore, we have a degree of control over how much power may be diverted into the retro-reflected downlink, and may adjust it to achieve the fidelity of downlink tracking that we require.

### 3.4 Parameter Estimation

Estimates of certain signal and channel parameters are typically necessary for accurate data recovery. Slot and symbol synchronization utilizes estimates of the symbol timing offset $\delta$ in an error-tracking timing recovery loop. As forward error correction is applied to the uplink command data, the decoding of that data requires an estimate of the mean signal and background flux rates in order to form decoder log-likelihood ratios. Once in uplink tracking mode, the beacon signal is restricted to a small tracking subwindow $\omega_t$, and the process of uplink timing and data recovery may proceed. The up-down counter values over the pixels in $\omega_t$ must be added in
order to collect the combined signal power which is split over at least four pixels. The summed up-down counter statistics are given by $U_t = \sum_{i,j \in \omega_t} U_{i,j}$ and $V_t = \sum_{i,j \in \omega_t} V_{i,j}$. Examination of the up-down counter expected values in (11) and (12) leads to the following plausible estimates for the symbol timing offset $\delta$ and the mean signal counts per symbol $K_s = 4\lambda_s T_{slot}$:

$$\hat{\delta} = \begin{cases} 
\frac{V_t + U_t}{U_t + V_t} & U_t > 0, V_t > 0 \\
1 + \frac{U_t}{U_t + V_t} & U_t < 0, V_t > 0 \\
2 + \frac{U_t}{U_t + V_t} & U_t < 0, V_t < 0 \\
3 + \frac{U_t}{U_t + V_t} & U_t > 0, V_t < 0 
\end{cases}$$

$$\hat{K_s} = \begin{cases} 
\frac{1}{N} (U_t + V_t) & U_t > 0, V_t > 0 \\
\frac{1}{N} (-U_t + V_t) & U_t < 0, V_t > 0 \\
\frac{1}{N} (-U_t - V_t) & U_t < 0, V_t < 0 \\
\frac{1}{N} (U_t - V_t) & U_t > 0, V_t < 0 
\end{cases}$$

where $N$ is the number of symbols or beacon cycles over which the up-down counters are collected.

4. PERFORMANCE RESULTS

4.1 Simulation

Performance of the signal detection, centroiding, and parameter estimation algorithms was evaluated through a combination of analysis, computer simulation, and laboratory testing. Of these methods, computer simulation provides the most flexible method of parametrically predicting performance. Toward these ends, a Matlab simulation was developed encompassing uplink signal modulation, Earth and stray light modeling, flight detector statistical output modeling, and signal processing algorithms, as shown in Fig. 6. The simulation includes an ideal two-dimensional Gaussian approximation to the Airy signal intensity pattern on the detector array, as well as a numerically integrated model of the Earth whose shape can be adjusted based upon the angle of illumination from the Sun. The detector pixels are assumed to collect the incident photons over the extent of the pixel field-of-view scaled by the detector fill factor, but a true spatial model of the lenslet array is not included. In the worst case, the spacecraft is at far range, leading to very low signal flux at the spacecraft, and the Earth is fully illuminated from the spacecraft point-of-view. We model a case in which the uplink beacon is 5 kW average power and the spacecraft is 2.7 AU from the Earth, leading to a detected beacon signal count rate of approximately 25,000 counts/sec/pixel (limited to about four pixels), and a detected Earth background count rate of approximately 100,000 counts/sec/pixel, assuming the parameters listed in Table 1.

The performance of the signal detection algorithm and decision statistic may be obtained by testing the probability of false alarm and probability of missed detection via a Monte Carlo simulation in which a signal is repeatedly placed either within a subwindow or outside of it, and the resulting decision statistic is computed and...
then compared to the appropriate threshold given in (22). Figure 7 shows the probability of missed detection using the modified square-law statistic as a function of integration time and background flux for probability of false alarm set to $10^{-6}$ and $10^{-3}$, for the link parameters listed in Table 1. We observe from these plots that an integration time on the order of 20 ms per search step is sufficient to reliably detect the beacon when the total background flux over the array (dominated by Earth radiance) is on the order of $10^7$ detected counts/sec. Once the background flux starts exceeding this level, longer integration times are needed, increasing the overall acquisition time. The effect of blocking was not considered in these particular simulations of the missed detection probability.

![Figure 7](image_url)  
*Figure 7. Probability of missed detection for the uplink beacon signal as a function of (a) integration time, and (b) background flux over detector array.*

Performance evaluation of uplink beacon centroiding is critical, as the error in knowledge of the beacon position is a dominant contributor to the downlink pointing error and, consequently, the downlink losses. The centroid error consists of both bias and jitter components, which we measure through Monte Carlo simulation under a variety of conditions, including different beacon positions within ±0.5 pixel from the crosshairs of a 4 × 4 centroiding subwindow located at the center of the detector array. The beacon is offset from the center of the full Earth, so that the Earth center-of-mass is not coincident with the beacon location. Figure 8 shows

**Table 1. Parameters used in uplink simulation and testing**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>uplink wavelength</td>
<td>1.064 µm</td>
</tr>
<tr>
<td>spacecraft range</td>
<td>2.7 AU</td>
</tr>
<tr>
<td>average uplink beacon power</td>
<td>5 kW</td>
</tr>
<tr>
<td>beacon irradiance at flight terminal</td>
<td>4.6 pW/m²</td>
</tr>
<tr>
<td>Earth radiance</td>
<td>0.0087 W/(cm²·sr·µm)</td>
</tr>
<tr>
<td>stray light radiance</td>
<td>$8.7 \times 10^{-5}$ W/(cm²·sr·µm)</td>
</tr>
<tr>
<td>modulation extinction ratio</td>
<td>20 dB</td>
</tr>
<tr>
<td>beacon/command channel slot width</td>
<td>65.536 µsec</td>
</tr>
<tr>
<td>aperture diameter</td>
<td>22 cm</td>
</tr>
<tr>
<td>filter bandwidth</td>
<td>1 mm</td>
</tr>
<tr>
<td>receiver optical loss</td>
<td>3.24 dB</td>
</tr>
<tr>
<td>detector fill factor</td>
<td>75%</td>
</tr>
<tr>
<td>array size</td>
<td>32 × 32</td>
</tr>
<tr>
<td>pixel field-of-view</td>
<td>7.8125 µrad</td>
</tr>
<tr>
<td>detection efficiency</td>
<td>40%</td>
</tr>
<tr>
<td>detector pixel dark flux</td>
<td>8000 counts/sec/pixel</td>
</tr>
<tr>
<td>detector blocking time</td>
<td>2.048 µsec</td>
</tr>
</tbody>
</table>

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the expected values of the modified square-law centroid algorithm root-sum-square (RSS) bias and jitter as a function of the X and Y beacon positions, in the absence of blocking. We see that the RSS bias is symmetric and that its expected value is zero at the crosshairs and centers of pixels, due to the spatial symmetry of the signal model. Conversely, the RSS jitter is maximum at the pixel crosshairs. The jitter is also not symmetric because the beacon is offset from the Earth center, whose flux contributes to the centroid jitter via the modified square-law statistic variance, but not to the centroid bias which depends upon the expected value of the modified square-law statistic.

Figure 8. Analytically calculated uplink centroid estimation error using modified square-law statistics in the absence of detector blocking, shown as a function of beacon position within ±0.5-pixel of tracking subwindow crosshairs: (a) RSS bias (b) RSS jitter

In Figure 9 we show uplink beacon centroiding simulation results when the beacon is positioned at the pixel crosshairs, with and without detector blocking, as a function of integration time (the time over which the centroiding statistics are collected). The Gaussian blocking model described in Section 2.2 is implemented in the simulation. We compare the performance of the modified square-law centroid with that of the conventional up-count centroid. We again see that the modified square-law centroid outperforms the up-count centroid in terms of bias but not jitter. We also see that for this case blocking affects the modified square-law centroid more than the up-count centroid, increasing the error terms by 0.1 to 0.2 µrad at lower integration times. However, even with blocking, the total centroid error (bias plus jitter) using the modified square-law statistic is within 1 µrad for integration times longer than about 17 ms (less than 60 Hz update rates).

The accuracy of the symbol timing offset and signal count estimates given in (25) and (26) was also evaluated via simulation as a function of integration time for the parameters in Table 1. A typical rule-of-thumb for minimal decoder loss is to achieve an RMS timing error of less than 0.1 slot. Figure 10 shows that this level of error is easily achieved at integration times of greater than 10 ms for the nominal background radiance level. When the background radiance is increased by an order of magnitude, this level can be achieved by increasing the integration time. Similarly, under nominal conditions, the mean signal count may be estimated to a less than 10% error for integration times of 20 ms or longer.

4.2 Laboratory Tests

The DSOC photon counting camera testbed is designed to emulate the channel conditions under which the flight terminal is expected to operate. By mimicking the signal and detector configuration, the testbed provides parametric test capability of both the photon counting detector array and the signal processing algorithms described here. The testbed projects a modulated 1064nm laser simulating the DSOC uplink laser, a CW 1550 laser simulating the DSOC downlink laser, and a white light background source onto the photon counting camera (see block diagram in Fig. 11). A commercial photon counting camera (PCC) detector array hybridized to a
readout integrated circuit \(^6\) was used in the results presented here. The photon counting array consists of 1024 pixels arranged in a 32x32 grid with 100 \(\mu\)m spacing, each pixel having a circular 16 \(\mu\)m diameter photosensitive region.

Between both the 1064nm and 1550nm laser sources and the photon counting camera are optics designed to provide adjustability to the projected laser spots. The optics are designed to project a spot size of approximately 4 pixels (2x2) for a 100nm pixel pitch design for the photon counting camera to emulate the design expectations for the DSOC flight terminal. These optics may be changed as needed to adjust the spot size. Filter wheels with neutral density attenuators provide order-of-magnitude control of flux levels from each of the sources, while fine tuning of flux levels is achieved by adjusting the connections of the laser fiber coupling. Kinematically mounted fold mirrors allow for relative spot positioning between the two lasers on the PCC image plane.

The 1550nm laser is a continuous source, while the 1064nm laser is connected to a modulator. The modulator is driven by a set of FPGA-based electronics which implements the uplink beacon signal format described in Section 2.1. The background source contains a variable output LED for adjusting flux levels. Additionally, a
A dichroic combines the background earth projection and the 1064nm laser source as would be seen by the DSOC flight terminal during operation. Finally, the detector array is mounted to a computer-controlled X-Y positioner stage which provides sub-pixel translation, needed to investigate the effects of spatial nonuniformities in the detector array on the performance of the algorithms as well as intrapixel effects.

The photon counting camera used in the laboratory has a $32 \times 32$ array of avalanche photo-diodes (APDs), co-packaged with a read-out integrated circuit (ROIC). The ROIC manages the biasing and quenching requirements of the APDs, and records photon arrival times at each of the pixels to 1 nsec accuracy. For the low data rates used in this experiment, such timing accuracy is not necessary, so a second set of ROIC outputs is used that reports the absence or presence of photon arrivals over approximately $2 \mu sec$ intervals for each pixel, as described in Section 2.2.

These data are transferred from the ROIC to a Field Programmable Gate Array (FPGA), where the initial data reduction is performed. The high-speed portions of four algorithms are implemented in Verilog: two for performing centroiding on the modulated uplink beacon (one at an unknown location anywhere on the array, and the second at a known location), one for demodulating the received uplink data, and one for centroiding on the downlink laser signal.

During uplink beacon acquisition, the received laser spot may appear anywhere on the detector array. Hence, the modified square-law statistic given by equations (8) through (10) and (17) is computed at a 60 Hz rate for every pixel in the array. In the hope that the beacon centroid lies close to the pixel for which $W_{i,j}$ is greatest, this pixel is taken as the center of a $3 \times 3$ window, and the centroid is calculated using (24). For convenience in implementation, the FPGA computes the numerators and the common denominator of these fractions in 32-bit integer arithmetic, and passes these values to a microprocessor, where the division operations are performed by C-language software. It is also the responsibility of the software to validate the centroid estimate based on the magnitude of the centroid denominator, and on the consistency of the centroid estimate over time.

After beacon acquisition, better performance of the centroid algorithm can be achieved by placing the beacon spot near the crosshairs between four pixels. The advantages are several. First, as shown in Figure 12, the algorithm is most sensitive to spot motion on the pixel boundaries, due in part to the algorithm itself and in part to the geometry of the photosensitive area of each pixel. Second, this spot placement allows the use of a $2 \times 2$ window instead of a $3 \times 3$ window, thus collecting fewer background photons. Third, it permits selecting
a particular $2 \times 2$ window, where the pixels have particularly good detection efficiency and low dark count rate. For these reasons, a second beacon centroiding algorithm is implemented in the FPGA, and it performs the same centroiding calculations in (17) and (24), but over a specific $2 \times 2$ window as specified by the microprocessor.

![Figure 12. Measured centroid X-coordinate vs. uplink spot displacement across detector array](image)

Rather than pointing the downlink laser directly at the location of the uplink beacon, a point-ahead angle is included to allow for motion during the round-trip light time. To permit closed-loop control of this point-ahead angle, a small portion of the downlink laser signal is redirected onto the APD array, and the centroid of this spot is computed as well. The modulation rate of the downlink laser is far faster than the $2\mu$sec rate at which the APD is monitored, and so it appears as an unmodulated spot. Hence, the downlink centroiding algorithm can only use the sum statistic of (10). During downlink transmission, the uplink beacon spot is driven to a pixel crosshair, and the point-ahead angle is known, and so the location of the downlink laser spot is also known to the open-loop accuracy of the point-ahead mirror. Thus, the downlink centroiding algorithm uses a $3 \times 3$ window at a location specified by the processor.

Finally, the optical uplink data is also detected by the PCC and demodulated by the FPGA. As described in Section 3.4, detected counts from the PPM-modulated signal are summed over the four pixels in the specified $2 \times 2$ tracking window. Slot timing is determined by a tracking loop that consists of an error function related to the symbol timing offset estimate given in (25) and a low-pass filter. In this way, the FPGA reports the number of photons detected in the two PPM slots of each symbol. These slot statistics are simply stored for later analysis and processing in this implementation. In a future implementation, it is intended that they would be drive a soft-symbol decoder for the underlying error correcting code.

For the laboratory test results presented here, the beacon laser spot was displaced from the center of the emulated Earth by approximately one pixel in each of the X and Y dimensions, representing a case in which the uplink transmitter station location is offset from the center of the full Earth when seen from the spacecraft. Figure 13 shows images captured from a single 60 Hz output from the FPGA processing described above. Figure 13(a) is the up-count output, showing the Earth image with the beacon spot, the downlink spot, and other variations in pixel output levels due to dark counts, stray light, etc. (including a “hot” pixel). Figure 13(b) is
the modified square-law output, which has effectively mitigated the background and reveals only the $2 \times 2$ uplink beacon.

![Figure 13. 32x32 detector array FPGA output with uplink beacon, downlink signal, and Earth emulation, showing (a) total detected counts over 17 ms (b) modified square-law statistics over 17 ms](image)

Using the setup shown in Figure 11 and the spatial configuration shown in Figure 13, the uplink and downlink centroids were calculated with different levels of Earth flux, ranging from zero up to 240,000 detected counts/sec/pixel. The uplink beacon flux and downlink flux were held constant at approximately 100,000 counts/sec and 200,000 counts/sec, respectively. Figure 14 shows the mean and RMS jitter values for the uplink centroid estimates as a function of the estimated Earth flux, for centroid calculations using the modified square-law statistics and the up-count statistics. From Figure 14(a), we see that the mean estimated position from the up-count centroid shifts in value as the Earth flux increases, while the modified square-law centroid position remains constant. This demonstrates that the modified square-law centroid estimate is not biased by the Earth background. Figure 14(b) shows the RMS jitter as a function of Earth flux. The up-count centroid jitter decreases with Earth background due to the increase in total flux, while the modified square-law centroid jitter increases. Simulations were run for the conditions under which these lab tests were conducted. The Gaussian blocking model was used in the simulation when the Earth flux exceeded $1.5 \times 10^5$ counts/sec/pixel, while the Poisson model was used in the lower flux cases. The simulated performance shows reasonable correspondence with the measured results, which demonstrate the impact of blocking upon centroid jitter. Plots of downlink centroid results are not shown here, but were measured to be stable and constant, with the jitter not exceeding 0.1µrad.

5. CONCLUSIONS

Signal processing algorithms were presented for deep-space optical uplink beacon acquisition, centroiding, and parameter estimation, using a photon-counting detector array. Descriptions of the uplink beacon modulation and flight terminal detector array concept were provided, along with statistical models of the detector output, including blocking. Monte Carlo simulation and laboratory test results using a commercial 32 × 32 photon counting camera were evaluated parametrically, showing how uplink centroiding accuracy varies with background conditions for realistic system parameters. The results demonstrate that the DSOC acquisition and tracking concept using a single photon counting detector array is capable of achieving the high acquisition probabilities and sub-microradian centroiding accuracy needed for deep space optical links.
Laboratory detector testbed measured centroid

(a) Position estimate in pixels
(b) RMS jitter in urad

Figure 14. Laboratory testbed centroid estimation results for 32x32 single photon counting detector array, shown as a function of Earth flux per pixel, and compared with simulation model. (a) Position estimate in pixels (b) RMS jitter in urad

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REFERENCES
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