ADAPTIVE OPTICAL ARRAY RECEIVER FOR COMMUNICATING THROUGH ATMOSPHERIC TURBULENCE

Victor Vilnrotter and Meera Srinivasan

INTRODUCTION

In this article, we describe a novel adaptive optical array receiver designed to improve ground-based reception of optical signals. The receiver is used to collect most of the incoming signal energy while at the same time rejecting most of the interfering background noise collected by the receiver. This requires a detector array placed in the focal-plane of the receiving telescope that operates jointly with a special purpose signal processing assembly. The optimum processing method is to estimate the signal and background energies over each detector element in real-time, compute an optimum numerical multiplier called a "combining weight" to be applied to the output of each detector element, and sum the weighted outputs. However, for large arrays, these operations can become difficult to carry out at the required speeds; hence a simpler, suboptimum "adaptive synthesized single detector" array receiver is also examined. A breadboard implementation of this array receiver, employing a 16-element photomultiplier (PMT) array and built by the Processor Systems Development Group (Section 335), is shown in Figure 1. With the performance of both the optimum and suboptimum array evaluated, the two receivers were shown to have comparable performance under operating conditions of interest. This article describes the atmospheric optical communications problem, an explanation of the algorithms needed to make these two adaptive receivers work properly, and a graphical description of their performance in terms of average probability of error.

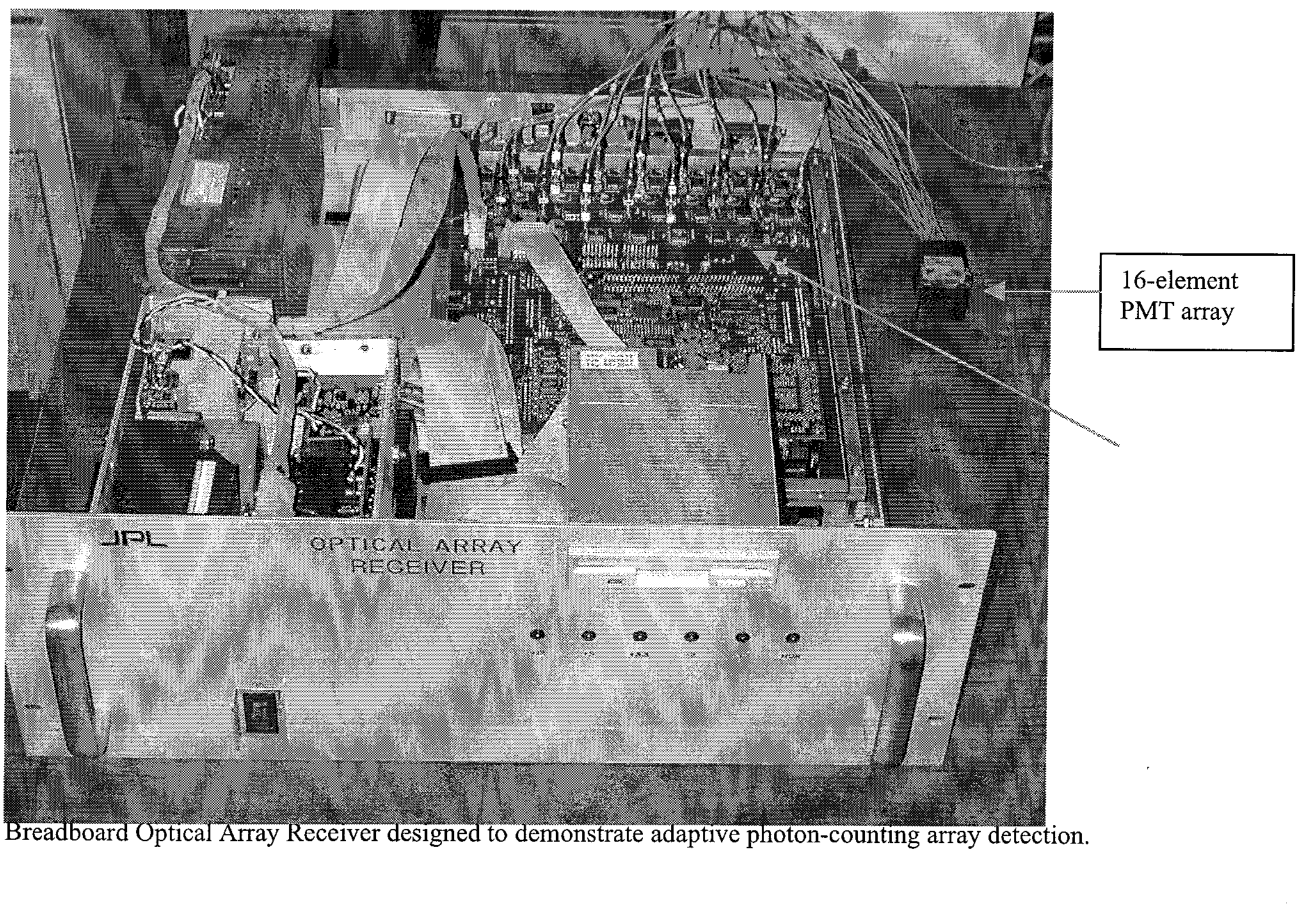

Figure. 1. Breadboard Optical Array Receiver designed to demonstrate adaptive photon-counting array detection.

Atmospheric Effects
Ground-based reception of optical signals from space suffers from degradation of the optical signal field caused by atmospheric turbulence. This leads to a reduction in the effective diameter of the receiving telescope, and to random fluctuations of the receiver's point spread function (PSF) in the focal plane (the PSF describes how the signal energy is distributed in the focal-plane). Under ideal conditions, a very small detector could be used to collect virtually all of the signal energy contained within the diffraction-limited PSF in the focal-plane, while at the same time spatially filtering out most of the background radiation. However, atmospheric conditions rarely permit diffraction-limited operation of large telescopes. Even under "good" nighttime-seeing conditions, the phase of the received signal field tends to become uncorrelated over distances greater than 20 centimeters (cm), deteriorating to as little as 2-4 cm during the day [1]. Under these conditions, the dimensions of the PSF in the focal-plane tends to increase inversely with coherence length. This is as if the dimensions of a diffraction-limited telescope were correspondingly reduced. The telescope still collects all of the signal energy propagating through its physical aperture, but the signal energy is redistributed into a much larger spot in the focal-plane.

An example of the random redistribution of signal energy in the focal-plane due to turbulence is shown in Figure 2, superimposed on a 16X16 array of detectors represented by dashed lines. By comparison, an ideally focussed spot would be mostly contained in a single-detector element.

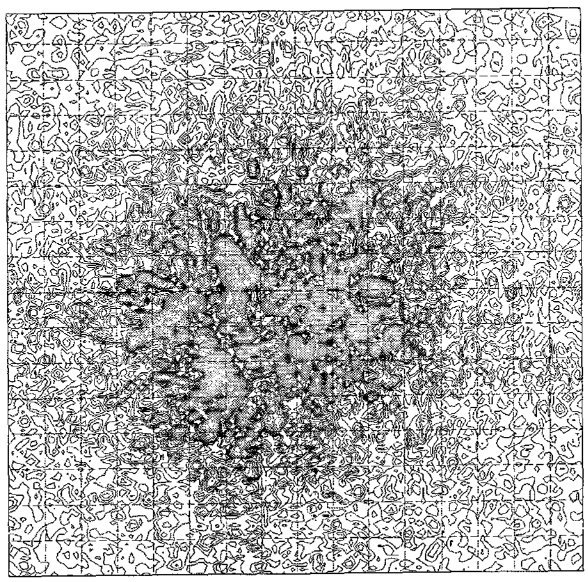

Figure. 2. Contour plot of instantaneous focal-plane signal distribution (covering 16X16 array) due to atmospheric turbulence: 4 cm coherence length

Optical Array Receiver Design: In order to collect most of the signal energy, the dimensions of a single optical detector must be made large enough to encompass the turbulence-degraded point-spread function as well as its random excursions in the focal-plane, which tend to change on time-scales of 10-100 milliseconds. However, a large detector implies a large receiver field-of-view. This in turn implies a corresponding increase in the amount of background radiation admitted into the receiver. That, in turn, degrades communications performance. These problems are effectively mitigated by the use of a high-speed photon-counting detector array together with high-speed digital electronics capable of performing the signal-processing functions required for optimum or near-optimum receiver performance.

A conceptual block diagram of an optical photon-counting array receiver is shown in Figure 3. The receiver consists of a collecting aperture and optics to focus the collected fields onto the focal-plane, where a detector array counts individual photons generated by the impinging fields. The output voltages from every element of the array are converted to numbers, which are then processed by a high-speed digital signal-processing assembly that performs the required mathematical operations in order to optimize receiver performance.

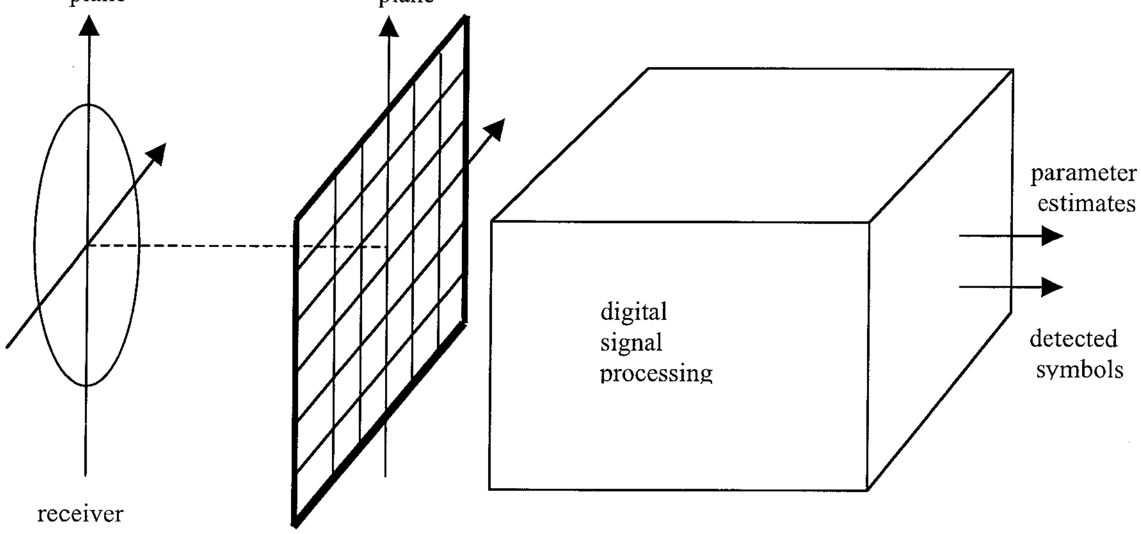

Figure. 3. Conceptual block diagram of optical "photon-counting array" receiver.

OPTICAL DIRECT DETECTION WITH FOCAL-PLANE ARRAYS

It has been shown in [2] that optical fields composed of signal plus multimode background fields generate randomly occurring pulses. These are approximately distributed—according to the Poisson probability density function—at the output of an ideal "photon-counting" detector. This model is reasonable for communications systems operating even at megabit per second rates. It also justifies the use of a relatively simple Poisson model, leading to mathematically tractable solutions. Using this model, two detector array receiver algorithms have been investigated for use with a particular form of optical signaling considered for deep-space communications known as "pulse-position modulation" (PPM), namely algorithms based upon an optimum detector array receiver and an "adaptive synthesized detector" subarray receiver.

The Optimum Detector Array Receiver

Pulse-position modulation (PPM) is an optical modulation format where a single optical pulse is placed into one of M consecutive time slots [4]. The received PPM symbol is decoded correctly if the value of the measurement corresponding to the signal-slot exceeds the measurement value from every other (non-signal) slot. The optimal photon-counting array observable consists of a numerically weighted sum of all detector outputs, where the numerical weight for each detector element is a logarithmic function of the ratio of signal and background photon intensities. A single detector can be synthesized from the array by setting all of the weights equal to one. Limiting cases corresponding to receivers employing such a single photon-counting detector will also be considered for comparison.

The "Adaptively Synthesized Detector" Subarray Receiver

In analyzing the optimal array, it was observed that detectors containing much more background energy than signal energy do not contribute significantly to the error probability, since the output of these "non-signal" detector elements are multiplied by weights that are very close to zero. This observation suggests the following suboptimum decoding algorithm which results in a greatly simplified receiver structure: list the detector elements starting with the one containing the most signal energy, followed by every other detector ordered according to signal energy. Compute the probability of error for the first detector element plus background, then form the sum of signal energies from the first two detector elements (plus background for two detector elements), and so on, until the minimum error probability is reached. Each of these sets of detectors may be considered to be a single detector, so that no weighting is applied to account for variations in the signal distribution over the detector elements included in a given set. The set of detector elements that achieves the minimum probability of error is the best "synthesized single detector" matched to the signal intensity distribution. In effect, the optimum logarithmic weights have been partitioned into two classes: "large" weights were assigned the value one, while "small" weights were assigned the value zero. We will show that this simple partitioning achieves near-optimum performance in low to moderate background environments, but with greatly reduced decoder complexity. However, this straightforward process of performing the optimization by actually calculating the error probabilities for each partial sum of detectors is not practical. Some practical methods for approximating this procedure are described in greater detail in [5].

NUMERICAL RESULTS

Both analytical calculations and computer simulations were performed in order to obtain *PPM* error probabilities for the optimally weighted array and the adaptive synthesized detector subarray. In order to generate spatial distributions of the signal incident upon the detector plane, sample fields were generated using computer simulations as described in [6], resulting in a matrix of complex signal amplitudes. For the simulation, an atmospheric correlation length of $r_0 = 4$ cm was assumed, which implies that the results should apply to any receiving aperture that is much greater than this correlation length [1]. The field intensity generated in the detector plane by the simulation was then integrated over the elements of a 16X16 detector array which encompassed the signal distribution in the detector plane. Constant average background energy was assumed over each detector element.

For a given sample function of the signal intensity distribution, the average signal energy over the 16X16 = 256 detector elements was sorted in decreasing order, and *M*-ary *PPM* symbol error probabilities were calculated for increasing numbers of detectors, starting with the first detector. The lowest curve in Figure 4 shows the symbol error

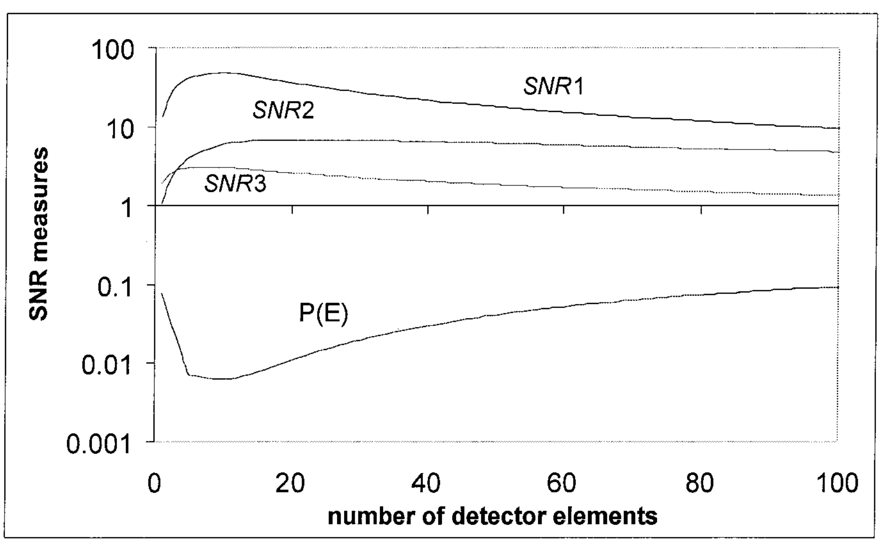

Figure. 4. Comparison of the optimum number of detector elements and numbers predicted by the three *SNR* measures.

probability for binary *PPM* ($M = 2$) as a function of the number of detector elements used, for the case $K_s = 10$ and $K_b = 0.1$ (that is, total average signal photons absorbed by the entire array is 10, average number of background photons *per detector element* is 0.1). It can be seen that for this case the smallest error probability of 0.0049 is achieved by assigning unity weight to the first 15 detector elements containing the greatest signal intensities, and zero to all the rest. The other curves correspond to various "easily computable" functions that attempt to predict the best number of detector elements, as described in the "Adaptively Synthesized Detector" Subarray Receiver paragraph above, without actually having to compute error probabilities.

Symbol error probabilities for binary *PPM* (M=2) are shown as a function of total average number of absorbed signal photons in Figures 5a and 5b, for the following cases:

- When the optimum number of "0-1" weighted detector elements are used
- Simulation of the optimally-weighted array
- When all 256 detector elements are given unity weight (synthesizing a large, nonadaptive single-detector element)
- When an ideal "adaptive optics" system succeeds in concentrating all of the available signal energy into a single-detector element, which then is the only detector element observed by the receiver.

The error probabilities computed in Figures 5a and 5b indicate performance gains by the "adaptive synthesized detector" subarray over a single "large" non-adaptive detector of 2 and 2.8, respectively. This is at an error

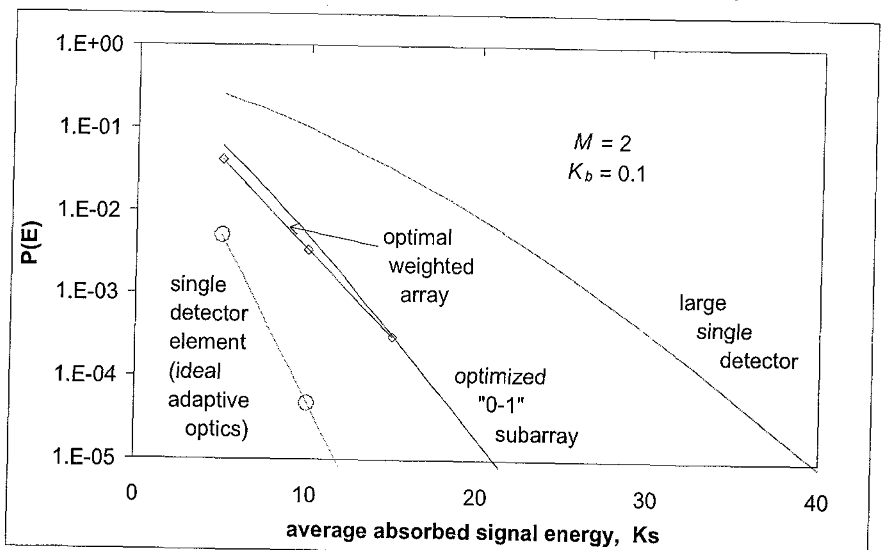

Figure. 5a. Binary error probabilities for "large single detector", optimally-weighted array, adaptive

probability of 0.001, corresponding to 3 decibels (dB) and 4.5 dB of performance improvement for average background photon counts of 0.1 and 1.0. When compared to the ideal "adaptive optics" receiver that concentrates all of the collected signal energy into a single element of the array, the gains are 3.8 and 8.2, corresponding to 5.9 dB and 9.1 dB of improvement. Note that the optimally weighted array yields only about 0.3 dB improvement over the adaptive synthesized detector subarray at a symbol error probability of 0.001, even with very high background energy corresponding to $K_b = 1$ background photon per detector element per slot.

Similar gains have been demonstrated for 16-dimensional ($M = 16$) *PPM*, and documented in [5]. Results for higher dimensional *PPM* signaling including $M = 2$, 16 and 256 are shown in Figure 6, plotted in terms of the receiver's "photon efficiency" (ρ), which is defined as the number of bits of information transferred by each photon on the average. Although 256 PPM is of great interest for possible use in future deep-space optical communications, the computation of exact error probabilities for this case were prohibitively complex, hence only simulation results are shown for this case.

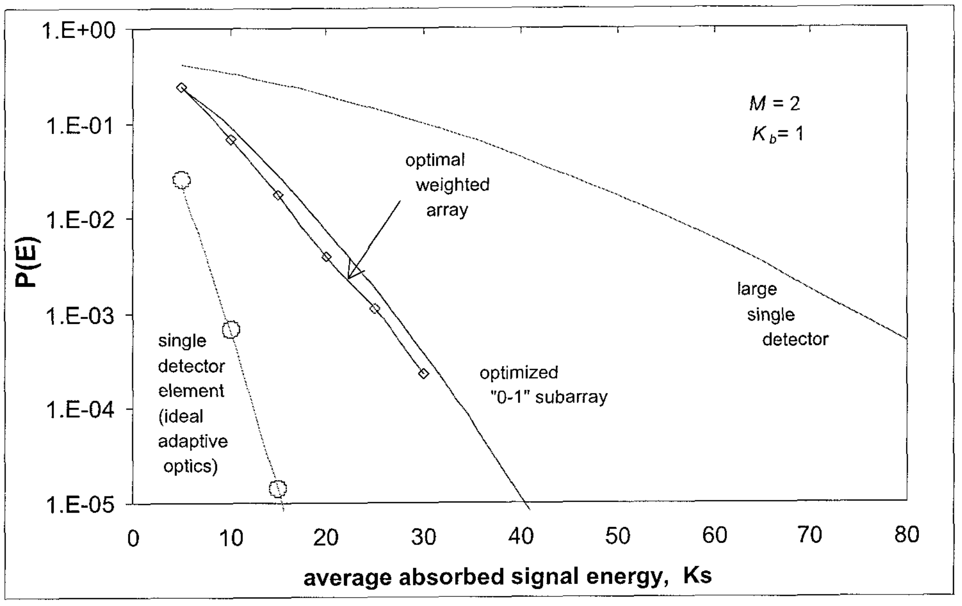

Figure. 5b. Binary error probabilities for "large single detector", optimally weighted array, adaptive synthesized detector subarray, and single detector element with ideal adaptive optics: $K_b = 1$

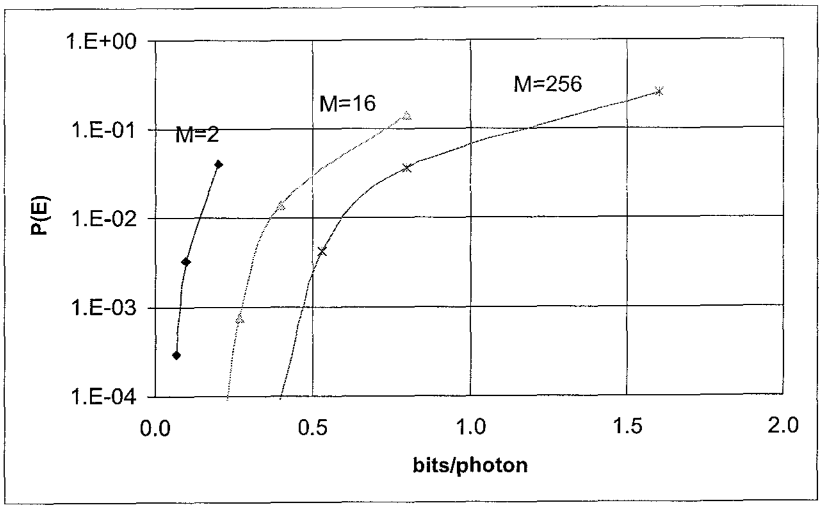

Figure 6. Simulated *PPM* bit error probability of optimum array receiver as a function of "photon efficiency" ρ (bits/photon), $K_b = 0.1$

It can be seen that with background levels of 0.1 photons per slot, photon efficiencies of approximately half a bit per photon ($\rho = 0.5$ bits/photon) can be achieved with 256 *PPM* signaling, at symbol error probabilities of 0.001–0.01. Additionally, coding can be applied to these *PPM* symbols to achieve even greater information efficiencies.

Algorithmic Optimization of the Number of Detector Elements

One problem with the approach described above for determining the optimum number of detector elements is that computation of the error probability for each increasing subarray requires a great deal of time, particularly when large detector arrays are used, which may not be feasible in a real-time operational system. As an alternative, numerical measures that take into account the number of detectors and the total average signal and background energies were constructed, to determine if simpler computations would suffice for determining the optimum number of detector elements in a real-time system. Three different measures were constructed and evaluated, each bearing some resemblance to a signal-to-noise ratio (*SNR)* although we emphasize that unlike for the case of additive Gaussian noise problems, in optical communications *SNR* is not necessarily a useful measure of performance. These three "easily computable" functions are defined in [5], and shown plotted in Fig 6 along with error probability. It can be seen that one of these functions, called SNR_1, yields performance comparable to that resulting from calculation of the exact error probability, but at a great savings in the required number of real-time computations.

Estimation of Signal Intensities

Finally, we note that the numerical results presented thus far were obtained under the assumption that the true values of the average signal and background photons absorbed by each detector element were known, and therefore the sorting of the detector elements was based upon the true signal energies. However, the signal energy distribution changes with time due to turbulence, although the background intensity can be considered constant in most applications. Therefore, we also examined a case where the signal energies were not known a priori, but had to be estimated from the observed detector outputs. The results of simulations in which actual Poisson deviates were generated for each array element, and the mean signal energies estimated from the observed outputs, are presented in [5].

For each detector array element, Poisson random variables were generated for the *M*-ary signal and background slots with average intensities obtained from computer simulations of the turbulent fields, plus a specified level of background light. These statistics were then sorted as before from largest to smallest. Both average number of signal and background photons were estimated from these statistics. We tacitly assumed that the actual background intensity can be estimated accurately. This is because it is essentially constant in the detector plane and because typically there is significant "dead time" between PPM symbols to allow for transmitter laser recovery [4]. This can be used to estimate the background intensity directly since no signal photons whatsoever are present during these intervals.

Simulation results using these estimation algorithms demonstrate that that real-time estimation of signal energies over the array does not result in any appreciable performance degradation. It is also shown in [5] that subarray optimization based on the simple SNR_1 algorithm mentioned above results in negligibly small losses, but succeeds in greatly reducing the complexity of the estimator.

SUMMARY AND CONCLUSIONS

A method of improving the performance of ground-based optical receivers in the presence of atmospheric turbulence through the use of photon-counting detector arrays and signal processing algorithms has been presented. Simulation results showed that use of an optimum array detection algorithm yields performance improvements of up to 5 dB relative to a single large detector designed to collect most of the turbulent signal, when operating in the presence of moderate to strong background radiation. It was also shown that in cases of interest, a simpler suboptimum algorithm performed nearly as well as the optimum algorithm, with considerable savings in computational complexity.

REFERENCES

1. Andrews, L.C. and Phillips, R.L., "Laser Beam Propagation through Random Media," *SPIE Optical Engineering Press*, Bellingham, Washington, 1998.
2. Gagliardi, R.M. and Karp, S., Optical Communications, John Wiley & Sons, New York, 1976.

3. Snyder, D.L., Random Point Processes, John Wiley & Sons, New York, 1975.
4. Vilnrotter, V.A., Simon, M.K. and Yan, T.Y., "The Power Spectrum of Pulse-Position Modulation with Dead Time and Pulse Jitter," *TMO Progress Report 42-133*, Jet Propulsion Laboratory, May 15, 1998.
5. Vilnrotter, V.A. and Srinivasan, M, "Adaptive Detectors for Optical Communications Receivers," *TMO Progress Report 42-141*, May 15, 2000.
6. Negrete-Regagnon, P., "Practical Aspects of Image Recovery by Means of the Bispectrum," *Journal of the Optical Society of America*, Vol. 13, No. 7, July 1996.