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Systematic experiments for proof of Poisson statistics on direct-detection laser radar using Geiger mode avalanche photodiode

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ABSTRACT

The single pulse detection and false-alarm probability in measuring time of flight (TOF) of laser pulse are caused by the creation of primary electrons in Geiger mode avalanche photodiode (APD). Measuring the detection and false-alarm probabilities with longer laser pulse than time bin and artificial noise source, we have experimentally proved that the creations of primary electrons in Geiger mode APD is Poisson distributed. It is also shown theoretically that there is little difference between smaller and larger laser pulse width than time bin cases on measurements of both detection and false-alarm probability.

1. Introduction

There are various methods for optical distance measurements (interferometry, time-of-flight and triangulation methods) [1]. For higher ranging capability, the laser radar system that measures TOF of laser pulse with the Geiger mode APD as detector has been developed by a few research groups due to its extremely high sensitivity [2–4]. The APD which is reverse biased above the breakdown voltage to operate in photon-counting mode, is the Geiger mode in which the primary electron generated by the absorption of a single photon initiates an avalanche process. The avalanche process constitutes the electrical current surge which has a sharp leading edge, allowing the high resolution timing [5].

However there are some negative aspects on Geiger mode APD as detector of the laser radar. First, the dark counts generated by thermal noises in the depletion region can cause the false-alarms. Second, the Geiger mode APD has the dead time after the detecting the photon in which the detector will not respond to any photons. In other words, the Geiger mode APD takes the time to reset after detecting and making the current surge which is the signal announcing the arrival of photons. The dead time typically varies from 10 ns to 1 μs depending on which material is used and how quenching circuit is designed. Assuming tens of kilohertz laser pulse repetition rate, multiple signals can be detected during the gate time in the case of short dead time (multi hit case), while only one signal can be detected during the gate time in the case of relatively long dead time (single hit case). If the Time to Digital Converter (TDC) can record only the first signal during the gate, then this laser radar belongs to single hit case even though the Geiger mode APD is capable of detecting multiple signals. In this paper only the single hit case is dealt in order to focus on the proving the theory that the generation of primary electrons in the Geiger mode APD follows the Poisson statistics.

In direct-detection laser radar, the number of receiver integrated primary electrons from a diffuse target follows a negative-binomial distribution [6,7]. When the number of photons received is much less than the speckle diversity, the Poisson distribution is a good approximation to the negative-binomial distribution [8].

In the next section, the direct-detection laser radar system with longer laser pulse than time bin is modeled with the assumption that the creations of primary electrons in the Geiger mode APD is Poisson distributed. It is shown that the calculated detection and false-alarm probabilities mostly do not depend on laser pulse width a few times larger than time bin, so that the experimental setup in Section 3 is regarded as appropriate. Section 3 explains the experimental setup for Poisson statistics on TOF measurements with Geiger mode APD and shows the results. The last section is summary.

2. Modeling

The mean number of primary electrons generated by single laser pulse scattered from the target is calculated analytically with laser range equation. And the mean number of primary electrons generated by noises including background lights and dark counts in the Geiger mode APD is assumed to be constant. Then, the Poisson statistics is used to derive the detection and false-alarm

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probabilities for Geiger mode APD considering laser pulse width larger than the time bin.

2.1. Laser range equation

The mean number of photons impinge on detector is the sum of laser signal photons and background photons composed of the sunlight both reflected from target and scattered by atmosphere in the field of view of laser radar system, and blackbody radiation from the target. The laser range equation model is illustrated in Fig. 1.

When transmitting a laser pulse of energy, E_T, the mean number of photons returning from a flat, diffusely reflecting extended target (Lambertian target) at distance R with the reflectivity ρ, $S_{P\text{-total}}$ is

$$S_{P\text{-total}} = E_T \frac{\lambda}{hc}\left(\frac{FOV}{\theta_T}\right)^2 \frac{\rho}{\pi}\cos\theta_{\text{target}}\frac{A_R}{R^2}\eta_T\eta_R\eta_A^2, \quad (1)$$

where

$$E_T = \int_{\tau_{\text{width}}} P_T(t)\,dt, \quad (2)$$

P_T is the transmitting optical power; τ_{width} is the width of laser pulse; h is Plank's constant; λ is the wavelength of laser pulse; c is the speed of light; FOV is the field of view of receiver; θ_T is the divergence angle of laser beam; θ_{target} is the angle of incidence of the laser beam relative to the surface normal; A_R is the area of the aperture of receiver; η_T is the transmission of transmitter; η_R is the transmission of receiver optics; and η_A is the one-way transmission of atmosphere between the target and receiver [9]. Let τ_{bin} be the time bin and S_{PE} be the mean number of generated primary electrons by laser pulse scattered by the target during τ_{bin}. Then S_{PE} is

$$S_{\text{PE}} = \int_{\tau_{\text{bin}}} P_T(t)\,dt\,\eta_Q \frac{\lambda}{hc}\left(\frac{FOV}{\theta_T}\right)^2 \frac{\rho}{\pi}\cos\theta_{\text{target}}\frac{A_R}{R^2}\eta_T\eta_R\eta_A^2, \quad (3)$$

where η_Q is the quantum efficiency of the Geiger mode APD.

In this paper, background photons rate is assumed to be constant so that during the gate time the mean number of generated primary electrons by background noise, N_{PE} is

$$N_{\text{PE}} = \tau_{\text{gate}}(\eta_Q N_{\text{BG}} + f_{\text{dark}}), \quad (4)$$

where N_{BG} is the solar background photons rate assumed to be constant and f_{dark} is the dark counts rate of the Geiger mode APD.

2.2. Poisson statistics

For a Poisson process, the probability that m events occur during times t_1 and t_2 is

$$P(m; t_1, t_2) = \frac{1}{m!}[M(t_1,t_2)]^m \exp[-M(t_1,t_2)], \quad (5)$$

where

$$M(t_1,t_2) = \int_{t_1}^{t_2} r(t)\,dt, \quad (6)$$

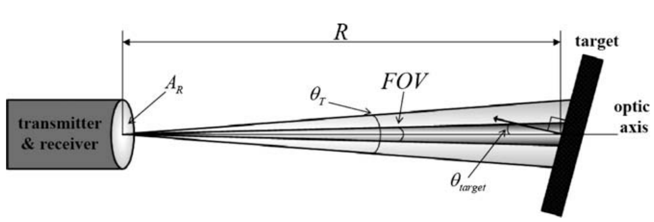

Fig. 1. The laser range equation model.

and $r(t)$ is the rate function of the process [8]. In the case of laser radar using Geiger mode APD, the creation of primary electron is the event and the mean rate of generation of primary electrons created by in coming photons between times t_1 and t_2. From Eq. (5), the probability that no primary electrons are created between times t_1 and t_2 is $\exp[-M(t_1,t_2)]$ and the probability that one or more are created is $1-\exp[-M(t_1,t_2)]$.

2.3. Detection and false-alarm probabilities

In the case of smaller laser pulse width than time bin, the single pulse detection probability at distance R, $P_{\text{detect-small}}$ is

$$P_{\text{detect-small}} = \exp(-fn)[1-\exp(-S_{\text{PE-total}} - n)], \quad (7)$$

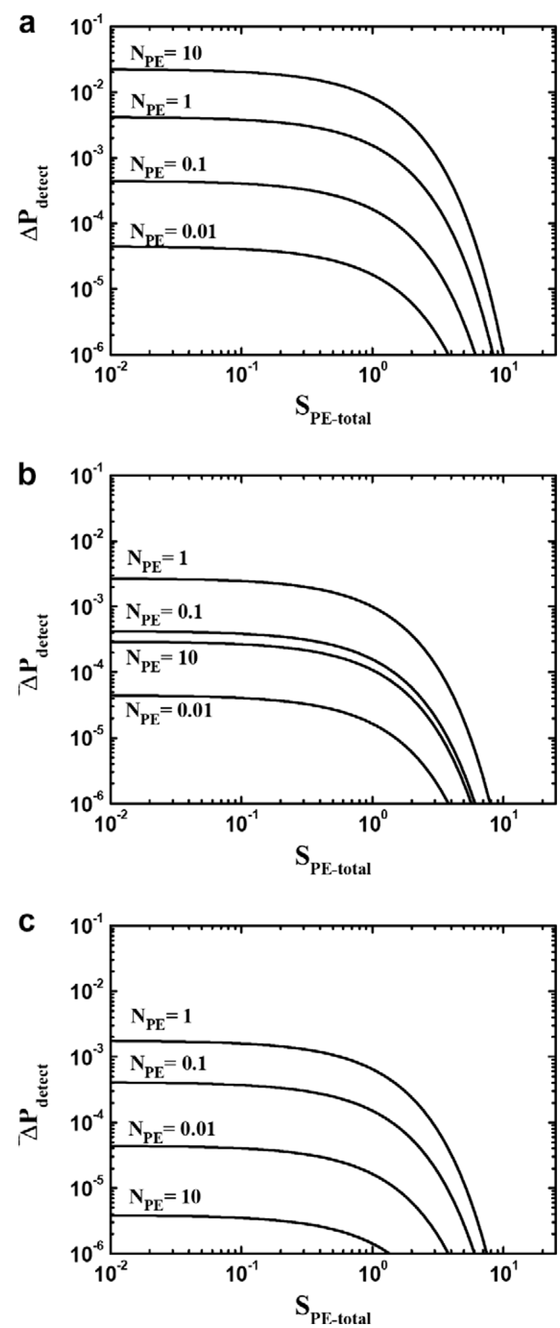

Fig. 2. The difference between single pulse detection probabilities of shorter and longer laser pulse cases versus the total number of primary electrons generated by laser signal. The curves are differentiated by, and labeled with, the N_{PE} in units of primary electrons per gate interval. (a) R = 10 m, (b) R = 75 m and (c) R = 145 m.