

Effect of Laser Pulse Characteristics on the Accuracy of Diffuse-Reflection Laser Ranging Systems (Postprint)

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Abstract

Ranging precision constitutes one of the most critical technical indicators for assessing the performance of diffuse-reflection laser ranging systems. Based on statistical theory and the operational principle of Geiger-mode avalanche photodiodes (PAD), numerical simulations were performed to investigate the effects of Gaussian waveform pulse width, echo intensity, and noise intensity on the ranging precision of such systems. The analysis specifically focused on ranging precision under single- and multi-photon-level echo signal intensities and various pulse widths, thereby providing a reference basis for laser selection and optimization of observation methodologies to enhance the observation precision of diffuse-reflection laser ranging systems.

Full Text

A Study on the Influence of Laser Pulse Characteristics on the Precision of Diffuse Laser Ranging Systems

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Abstract

Ranging precision is one of the most important technical indicators for measuring the performance of diffuse laser ranging systems. Based on statistical theory and the working principle of Geiger-mode avalanche photodiodes (GAPD), this

paper numerically simulates the effects of Gaussian waveform pulse width, echo intensity, and noise intensity on the ranging precision of diffuse laser ranging systems. The analysis focuses on ranging precision at single- and multi-photon echo intensity levels under different pulse widths, providing a reference basis for laser selection and optimization of observation methods to improve the observation precision of diffuse laser ranging systems.

Keywords: Diffuse reflection laser ranging; Ranging precision; Ranging accuracy; Laser pulse width; Echo intensity

1. Introduction

Satellite Laser Ranging (SLR) is one of the most accurate techniques for satellite orbit determination, and its observation data have been widely applied in satellite dynamics, space geodesy, geodynamics, and geophysics research fields [1]. With the development of SLR technology, the single-shot ranging precision for conventional cooperative targets has reached the sub-centimeter level [2]. However, traditional laser ranging is only applicable to cooperative targets equipped with retroreflectors. Most space objects in orbit are non-cooperative targets, such as space debris. To expand the application scope of laser ranging technology and leverage its high precision characteristics, space debris laser ranging has received significant attention worldwide, with multiple stations successfully obtaining measured data.

According to published data, the Stromlo SLR station in Australia uses a 50 cm telescope to track space debris, achieving a ranging precision better than 1.5 m [3]. The Graz station has obtained an average ranging precision of 50-250 cm [4]. The Shanghai Astronomical Observatory and Changchun Satellite Laser Ranging Station have achieved ranging precision better than 80 cm [6-7]. Yunnan Observatories has obtained an average data precision of 70 cm [9-10]. Numerous factors affect ranging precision, including timing device precision, main wave signal detection accuracy with constant-fraction discrimination, and detection accuracy of single-photon detectors with time walk compensation. However, most instrument-related effects on ranging precision can be reduced to the millimeter level after calibration [1].

In diffuse laser ranging, space debris surfaces exhibit diffuse reflection characteristics, which reduces echo intensity during ranging. To detect space debris echo signals, high laser pulse energy and repetition rate are required. However, due to current laser development and manufacturing limitations, it is difficult to achieve pulse widths at the hundred-picosecond level while meeting the energy and frequency requirements for diffuse laser ranging systems. Typically, lasers used in diffuse laser ranging systems have pulse widths around 10 ns.

This paper investigates the influence of laser pulse width and echo intensity on diffuse laser ranging precision based on SLR principles and timing sequences, without considering target shape modulation effects on laser pulse waveforms. Previous studies have analyzed laser radar system precision and accuracy based

on the detection probability distribution of Geiger-mode APDs [11-12]. However, these methods have certain deviations for SLR system precision analysis because subsequent data processing does not use all photon-triggered moments within the gate. Instead, identifiable echo data within the gate are selected for further processing.

2. Ranging Precision of C-SPAD Satellite Laser Ranging Systems

2.1 Detector Probability Model

C-SPAD (Single-Photon Avalanche Diode) is a Geiger-mode avalanche photodiode widely used in laser ranging systems. When the bias voltage reaches or exceeds the breakdown voltage, the detector achieves single-photon sensitivity. A photoelectron triggers an avalanche effect, significantly increasing the output current.

The principle of a satellite laser ranging system based on C-SPAD is shown in [Figure 1: see original paper]. The laser pulse is detected by a PIN photodiode to generate a main wave signal, which is sent to an event timer to record the main wave epoch t_0 . The control computer calculates the gate opening time based on target orbit prediction, and the range gate generator produces a gate signal for the C-SPAD to detect echo signals [13]. Whether triggered by noise or signal photons, the detector outputs a detection signal and shuts down. The detection epoch t_i is recorded by the event timer and sent to the control computer, which calculates the interval $t_i - t_0$ and compares it with predicted target data. The differences form a point cloud diagram for partial display. Data-dense regions are selected within certain distance windows, noise outliers are rejected for real-time monitoring [14], and the remaining data are used for subsequent processing.

2.2 C-SPAD Detection Probability Distribution

Without considering pulse broadening, the echo pulse temporal distribution is assumed to follow a Gaussian distribution. The photoelectron count as a function of time is given by:

$$n_{\text{sig}}(t) = \frac{S}{\sqrt{2\pi}\sigma} \exp\left[-\frac{(t - \tau_d)^2}{2\sigma^2}\right]$$

where S is the total number of photons in the echo pulse, σ is the standard deviation of the Gaussian function, and τ_d is the target epoch within the gate. The pulse width is taken as the full width at half maximum (FWHM) τ_{FWHM} , which relates to the standard deviation as:

$$\sigma = \frac{\tau_{\text{FWHM}}}{2.3548}$$

The noise primarily originates from uncorrelated background noise and detector dark counts, both assumed to be uniformly distributed. The average photoelectron count from noise is:

$$\bar{n}_{\text{noise}} = \eta n_b + n_d$$

where η is the detector's photon detection efficiency, n_b is the background photon count rate, and n_d is the dark count rate.

From the single-photon detection principle, the detection probability for any time interval T equals the probability of detecting at least one photon in that interval. For C-SPAD, this is:

$$P(T) = 1 - \exp \left[- \int_T (n_{\text{sig}}(t) + \bar{n}_{\text{noise}}) dt \right]$$

[Figure 2: see original paper] shows the triggered probability distribution in different time bins within the detector's range gate for various echo intensities, assuming a Gaussian pulse with 10 ns width. The probability distribution becomes more concentrated as echo intensity increases, improving ranging precision. For $S \ll 1$, the detector is more likely to be triggered by the leading edge of the input pulse, causing the peak probability to deviate from τ_d . For $S \gg 1$, the trigger probability distribution becomes more concentrated around τ_d .

The probability of noise triggering within the gate decreases over time. Before the echo signal arrives, the detection probability forms a minimum p_{min} . As the echo signal appears, a relative maximum p_{peak} forms. The larger the ratio $p_{\text{peak}}/p_{\text{min}}$, the more distinguishable the echo signal [15], facilitating extraction from noise.

In subsequent calculations, the echo signal is considered identifiable when its trigger probability exceeds P_{th} . The identifiable region is shown in [Figure 3: see original paper].

2.3 Ranging Precision and Accuracy Calculation

The range gate is divided into N time bins, each with interval Δt . The detection probability for the i -th bin is denoted as P_i . If the identifiable region spans from the K -th to M -th bin, the normalized probabilities are:

$$\tilde{P}_j = \frac{P_{K+j}}{\sum_{j=0}^{M-K} P_{K+j}}, \quad j = 0, 1, \dots, M - K$$

The expected trigger epoch within this region is:

$$E(t) = \sum_{j=0}^{M-K} \tilde{P}_j \cdot t_{K+j}$$

where t_{K+j} is the median time of the $(K + j)$ -th bin. The ranging accuracy is:

$$\text{Accuracy} = E(t) - \tau_d$$

From the variance-expectation relationship, the one-way ranging precision is:

$$\sigma_t = \sqrt{D(t)} = \sqrt{E(t^2) - [E(t)]^2}$$

3. Results and Discussion

[Figure 4: see original paper] shows ranging precision versus echo intensity and pulse width. Laser pulse width is a critical parameter affecting precision. Narrower pulses concentrate energy temporally, resulting in smaller photon time distributions and thus higher precision. At constant pulse width, stronger echo signals increase the probability of triggering C-SPAD at the pulse leading edge, improving precision.

When the pulse width is 10 ns and echo intensity is below 5 photoelectrons, the precision degradation due to pulse width is no more than 2.5 ns, corresponding to less than 75 cm in distance. According to Yunnan Observatories' published diffuse laser ranging precision [9-10], when echo intensity exceeds 5 photoelectrons, the precision due to pulse width is better than 1.6 ns.

[Figure 5: see original paper] shows ranging accuracy versus echo intensity and pulse width. At constant echo intensity, accuracy decreases as pulse width increases. At constant pulse width, stronger echo signals reduce accuracy because the increased probability of leading-edge triggering causes the detector to fire earlier than the target epoch within the gate. For a 10 ns pulse width and echo intensity of 20 photoelectrons, the accuracy is approximately -6.3 ns. This bias due to different echo intensities can be considered a systematic error. System delay calibration using ground targets at known distances under strong echo conditions, combined with real-time echo intensity monitoring during observations, can improve both precision and accuracy.

[Figure 6: see original paper] and [Figure 7: see original paper] show the effects of noise intensity on precision and accuracy. Lower noise yields higher precision (less data dispersion). At single-photon level with noise increasing from 10 kHz to 500 kHz, the precision difference is 0.12 ns. The impact on accuracy is minimal, with a difference of 0.145 ns for echo intensity of 20 photoelectrons when noise increases from 10 kHz to 500 kHz.

Without considering target shape effects, noise intensity has relatively little impact on precision and accuracy compared to echo intensity and pulse width.

While increasing laser energy alone improves precision, it reduces accuracy. Reducing pulse width effectively improves both precision and accuracy. When pulse width cannot be reduced, system delay calibration using ground targets at different echo intensities is necessary to improve precision without sacrificing accuracy.

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