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Range accuracy analysis of streak tube imaging lidar systems

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ABSTRACT

Streak tube imaging lidar (STIL) is an active imaging system that has a high range accuracy and a wide range gate with the use of a pulsed laser transmitter and streak tube receiver to produce 3D range images. This work investigates the range accuracy performance of STIL systems based on a peak detection algorithm, taking into account the effects of blurring of the image. A theoretical model of the time-resolved signal distribution, including the static blurring width in addition to the laser pulse width, is presented, resulting in a modified range accuracy analysis. The model indicates that the static blurring width has a significant effect on the range accuracy, which is validated by both the simulation and experimental results. By using the optimal static blurring width, the range accuracies are enhanced in both indoor and outdoor experiments, with a stand-off distance of 10 m and 1700 m, respectively, and corresponding, best range errors of 0.06 m and 0.25 m were achieved in a daylight environment.

1. Introduction

Streak tube imaging lidar (STIL) has attracted a great deal of attention in recent years because of its high range accuracy, wide range gate and high frame rate [1–3]. A typical STIL architecture is depicted in Fig. 1(a) and (b). The laser is projected into the scene as a fan beam, forming a strip-shaped footprint on the target. The scattered target return is imaged onto the photocathode by a camera lens and converted to electrons. This electron stream is then accelerated towards the phosphor screen (anode) via a high voltage applied between the photocathode and the screen. A pair of deflection plates with a time-dependent voltage is applied to give the electrons an offset that is proportional to the deflection voltage; thus, the strip images at different positions of the phosphor screen represent different echo times (i.e., target ranges). The phosphor image is usually captured by using a fiber optic coupled CCD [4,5]. As shown in Fig. 1(c), each column of the CCD image represents a time-resolved channel, while each row represents a time bin. A 3D image can be reconstructed from multiple pulses of a single-slit STIL (SS-STIL) by scanning the scene with the laser fan beam or by a scannerless modification called multiple-slit streak tube imaging lidar (MS-STIL). Compared to the MS-STIL, the SS-STIL has a wider range gate with the same CCD resolution [6] and thus can discriminate targets more efficiently [7]. Furthermore, the simple structure of the SS-STIL can help to obtain an in-depth analysis of the lidar characteristics.

Range accuracy is one of the most critical features of imaging lidar systems. Gleckler et al. reported that the achievable range error for a STIL system is based on the peak detection algorithm and can be estimated by [8–10]

$$\sigma_{range} = 0.6\frac{C\tau_{laser}}{SNR}, \tag{1}$$

where c is the speed of light; τ_{laser} is the pulse width of the laser, i.e., the full width at half maximum (FWHM) of the laser pulse profile; and *SNR* is the signal-to-noise-ratio for a single channel. The equation shows that the range accuracy only depends on the laser pulse profile and the *SNR*. However, according to the peak detection algorithm [9], the peak position (i.e., target range) is determined by the time-resolved signal distribution of one CCD channel, which is not only related to the laser pulse shape but also to the effect of blurring in the image. The range error is also directly proportional to the width of the time-resolved signal, including the effect of blurring. To quantitatively analyze the blurring of an image, a static blurring signal should be introduced. The static blurring signal is the intensity profile of one CCD channel when the STIL works in static mode, in which the deflection voltage is equal to a specified value. Consequently, research on the relationship between the range error and the width of the static blurring signal can help to produce a more realistic estimate of the range accuracy.

In this paper, we establish a model of the time-resolved signal distribution that includes both the laser pulse width and static blurring width and present a modified range accuracy analysis. We then perform a numerical simulation and indoor and outdoor experiments to validate the theory, with an emphasis on the effect

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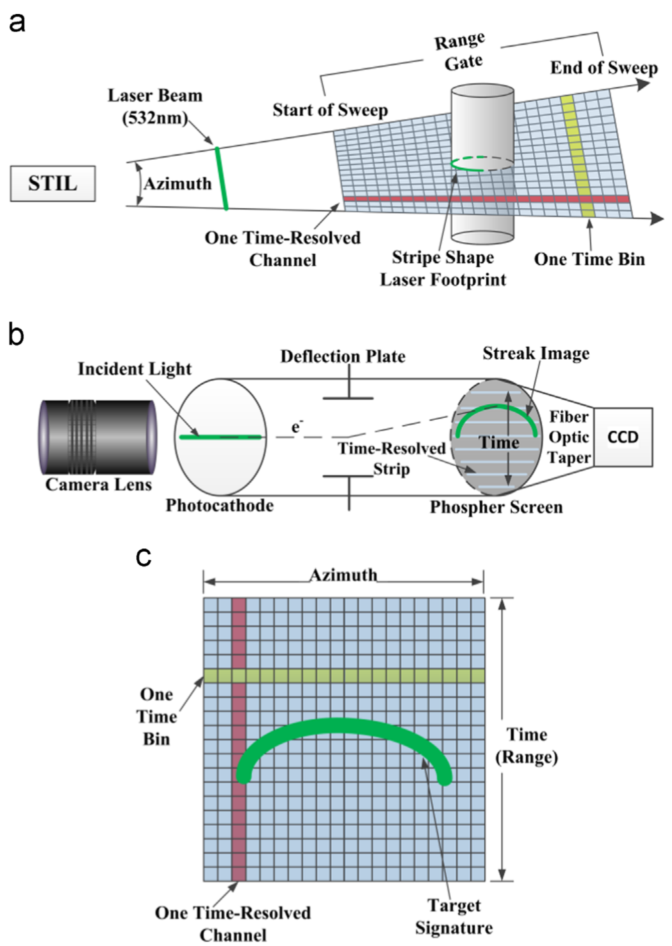

Fig. 1. (a) Schematic diagram of the streak tube imaging lidar data collection process. (b) Illustration of the work principle of the streak tube detector. (c) The streak image at the phosphor screen, as captured by CCD.

of the static blurring width on the range accuracy. By using the optimal static blurring width, range errors of 0.06 m and 0.25 m are achieved in indoor and outdoor experiments with stand-off distances of 10 m and 1700 m, respectively.

2. Theory

As depicted in Fig. 2, each laser pulse can be divided into a series of time slices, and the laser energy in each slice generates a corresponding blurring signal profile. When the blurring signal profiles are integrated with respect to time, the time-resolved signal is then formed. The width of the time-resolved signal is the most important factor for the estimation of the range accuracy and will be analyzed in the following section.

2.1. A. Laser pulse profile

Generally, the laser pulse profile, with a pulse width of τ_{laser} (FWHM), can be approximated using a Gaussian distribution [11]

$$P(t) = P_0 \exp\left[-\left(\frac{t}{\sigma_{laser}}\right)^2\right], \tag{2}$$

where P_0 is the maximum radiant pulse energy received by a given column of the CCD. It depends on the total laser pulse energy, the distance to the target, the atmospheric transmission, the reflectivity of the target, the angle of incidence on the target, the camera aperture, and the sensitivity of the streak tube and the CCD [12]. t is the time and σ_{laser} is the characteristic parameter of the laser pulse profile, which is given by

$$\sigma_{laser} = \frac{\tau_{laser}}{1.66}. \tag{3}$$

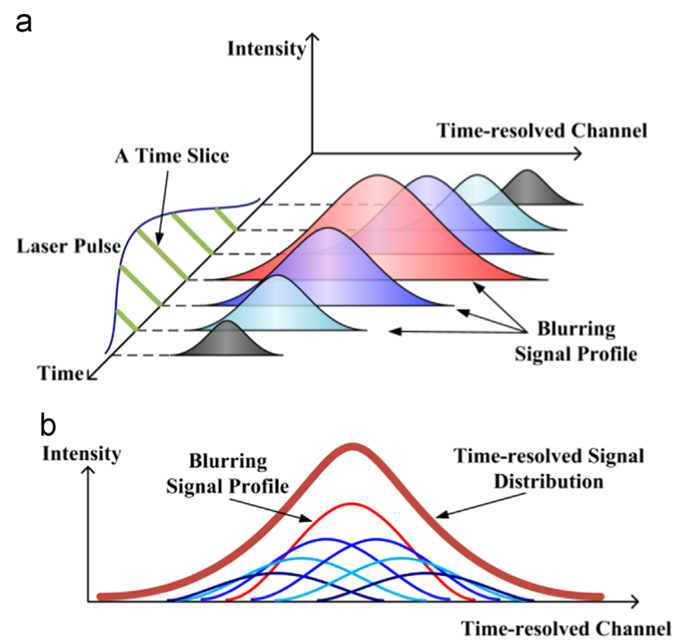

Fig. 2. The composition of the time-resolved signal. (a) The laser energy in each time slice generates a corresponding blurring signal with different peak positions in the time-resolved channel. (b) The time-resolved signal is formed by integrating all of the blurring signals.

2.2. B. Static blurring signal distribution

The streak tube can operate in both static and sweep modes. In sweep mode, the echo signal at different times will be deflected by the time-dependent voltage and imaged onto different time-resolved strips of the phosphor screen. In static mode, the deflection voltage equals a specified value and the STIL works only as an imaging device with no time-resolving function. The laser footprint will be directly imaged on the phosphor screen and then captured by the CCD. Because the strip-shaped laser footprint is very thin, an STIL with a limited resolution of the streak tube will result in a blurred raw image on the CCD. By measuring the intensity distribution along the CCD column in static mode, the static blurring signal can be obtained.

Fig. 3 shows a typical static streak image exhibiting the static blurring signal distribution with the following Gaussian fit

$$F(x) = A_{static} \exp\left[-\left(\frac{x - B_{static}}{\sigma_{static}}\right)^2\right], \tag{4}$$

where x is the pixel position of the time-resolved channel; A_{static} is the maximum intensity of the channel; B_{static} is the peak position, which depends on the deflection voltage; and σ_{static} is a characteristic parameter of $F(x)$ with units of pixels. If the pixel pitch of the CCD is given as d_{CCD}, the static blurring width (FWHM) is given by

$$\tau_{static} = 1.66\sigma_{static} d_{CCD}. \tag{5}$$

It's worth noting that τ_{static} is invariable with different laser pulse energies, as shown in Fig. 4.