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Noise modeling, evaluation and reduction for the atmospheric lidar technique employing an image sensor

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ABSTRACT

Atmospheric lidar signal, measured by the lidar technique employing an image sensor, suffers from sunlight shot noise, dark current noise, readout noise, and fixed pattern noise (FPN) of the image sensor. A noise model has been established to describe the noise characteristics and verified by evaluating lidar signals measured by an 808-nm Scheimpflug lidar system employing a CMOS image sensor as the detector. The sunlight shot noise and the photo-response non-uniformity (PRNU) noise that is one of the FPNs are found to be the primary noise sources of the lidar signal. The PRNU noise ratio is strongly dependent on the total illumination intensity of the image sensor and is minimized under high-light-level conditions. Thus, automatic exposure is suggested to achieve the best signal-to-noise ratio. Three different digital filters are employed to suppress the noise of the lidar signals, among which the Savitzky–Golay filter achieves the best performance. Moreover, a signal resampling method is proposed to improve the SNR for the near-range lidar signal. This work provides an in-depth understanding of the noise characteristics and proposes dedicated signal processing methods for atmospheric lidar techniques employing image sensors as detectors.

1. Introduction

Lidar techniques, based on the time-of-flight principle, have been extensively developed and widely employed for atmospheric remote sensing for decades [1–3]. The Scheimpflug lidar technique, based on the Scheimpflug principle [4,5], has been recently developed for atmospheric remote sensing by employing an image sensor as the detector [6–8]. The Scheimpflug principle provides a unique approach to achieve infinite depth-of-focus while employing large aperture optics for an imaging system. Large aperture optics is essential for developing atmospheric lidar techniques since atmospheric backscattering light is rather weak. As shown in Fig. 1(a), the plane of the transmitted laser beam, the lens plane and the image plane intersect into a single line. This way, the Scheimpflug principle is fulfilled and the atmospheric backscattering light can be clearly focused on a tilted image sensor. Thus, the Scheimpflug lidar technique can measure the range-resolved atmospheric backscattering signal utilizing compact high power laser diodes and highly integrated CMOS/CCD image sensors. Due to the advantages of low cost and robustness, the Scheimpflug lidar technique has been developed for various atmospheric applications, e.g., 24-h continuous measurements of atmospheric extinction coefficient or depolarization [9,10], and atmospheric background NO_2 monitoring during nighttime [11].

Two-dimensional (2D) image sensors with high frame rates, e.g., CMV2000 (CMOSIS) and S11071 CCD (Hamamatsu), are often employed in the Scheimpflug lidar technique in order to capture the full image of the laser beam that is transmitted into atmosphere. The on/off intensity-modulation of the laser diode is synchronized with the exposure of the image sensor. The "on" image includes the laser and the background. The "off" image is the background only. "On" and "off" images are recorded alternately, as shown in Fig. 1(b). The pixel-intensity curve, corresponding to the range-resolved lidar curve, is obtained by performing vertical binning, background subtraction and signal averaging on the recorded laser beam images, as shown in Fig. 1(c). The pixel information can be transformed to distance information by measuring the backscattering signal from a hard target with a known distance [7].

In addition to the atmospheric background noise, the Scheimpflug lidar technique suffers from additional noise sources in the image sensor. In previous studies, it has been found out that the signal-to-noise ratio (SNR) of the Scheimpflug lidar signal during nighttime is even worse than that in daytime with 20 ms exposure time [9], despite sunlight

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radiation being substantially larger in daytime. Moreover, the noise increases as the intensity of the measured lidar signal increases during nighttime measurements. The multiple noise sources and the abnormal noise characteristics are the main challenges in the processing of the Scheimpflug lidar signals. In recent years, noise evaluation and reduction have been extensively studied in conventional pulsed atmospheric lidar techniques [12–15], and quite a few digital filters have been proposed for signal de-noising of atmospheric lidar signals, e.g., empirical mode decomposition [16–18], wavelet analysis [19], Kalman filter [20], particle filter [21], and Savitzky–Golay (SG) filter [22]. However the characteristics of the noise sources in a Scheimpflug lidar have not been carefully studied yet.

This work aims at modeling and evaluating the noise sources for lidar systems employing image sensors, in the meanwhile providing an in-depth understanding about various noise sources as well as dedicated signal-processing methods. In following sections, we will first briefly introduce the Scheimpflug lidar system utilizing a CMOS sensor as the detector. In Section 3, a noise model for the Scheimpflug lidar technique is established by considering sunlight background noise and the sensor noise. Noise evaluation is then performed based on the experimental results measured in various atmospheric conditions in Section 4. Signal de-noising methods as well as a near-range signal resampling approach are investigated in Section 5. Finally, the conclusions are given and the future improvements on the SNR of the atmospheric lidar signal are discussed.

2. Experimental setup and measurements

2.1. The Scheimpflug lidar system

Noise modeling and evaluation are based on the experimental results measured by an 808-nm single-band Mie-scattering Scheimpflug lidar system developed by Dalian University of Technology [10]. Detailed specifications of the lidar system are shown in Table 1. We hereby briefly describe the principle of the setup. The laser beam of an 808-nm laser diode is collimated by a F6 refractor and transmitted into the atmosphere. The Scheimpflug lidar system employs a 200-mm diameter Newtonian telescope (f = 800 mm) to collect atmospheric backscattering signal and a 2D CMOS image sensor for light detection. Sunlight background is suppressed by a narrow-band 808-nm interference filter and a long-pass filter. Backscattering signals are recorded in a region of interest (ROI) with 2048 × 200 pixels, which is sufficient to capture the full image of the beam returned to the image sensor by atmospheric scattering (see Fig. 1(b)). The exposure time of the CMOS sensor may also be adjusted to study the noise level of different exposure times. Although the CMOS sensor is tilted 45° in the Scheimpflug lidar system, the pixel-to-pixel variation of the incident angle is rather small, i.e., ±0.3°, as the length of the CMOS sensor is much smaller than the focal length of the receiving telescope. Such a small variation of the incident angle contributes negligible effect on the lidar signal as well as the noise characteristics, which is thus not considered in this work. The unit of the output signal is transferred from the digital number (DN) to the photon count through the conversion efficiency. The conversion efficiency is estimated from the full well capacity (8600 electrons) and the quantum efficiency of the CMOS sensor, i.e., 80 photon counts/DN.

2.2. Atmospheric measurements

Atmospheric remote measurements were carried out in March and August 2017 under different atmospheric conditions, e.g., clean or polluted atmosphere during daytime as well as nighttime. Typical background signals (S_{BG}) and lidar signals (S_0) measured by the Scheimpflug lidar system are shown in Figs. 2 and 3, respectively. The signals have been averaged for 1000 times. The background signal varies significantly during daytime and nighttime, as can be seen in Fig. 2. During daytime measurements, sunlight background signal is rather strong even with a low (20 ms) exposure time, and the signal-to-background ratio is typically in the order of 1:100 under a sunny and clean weather. During nighttime measurement, the background signal S_{BG} mainly consists of the dark current signal of the image sensor (i.e., $P_D t$), which is equivalent to about 4.9 × 10^4 photon counts. As shown in Fig. 3, the lidar curve with the minimum background signal (the solid curve) shows the maximum noise level, whereas the SNR of the lidar curve with the strongest intensity and relatively small background signal (the dot curve) does not greatly over-perform the others (the

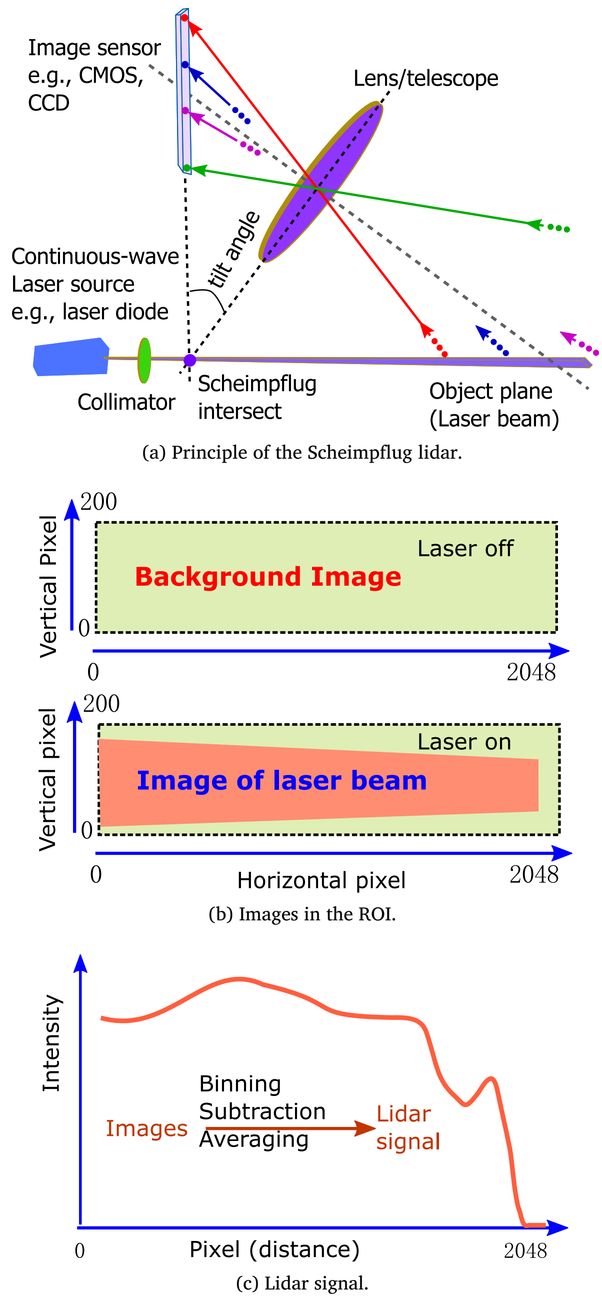

Fig. 1. (a) Principle of the Scheimpflug lidar system, the CMOS sensor is tilted to satisfy the Scheimpflug principle [7]. (b) Images in the Region Of Interest (ROI), recorded when the laser diode is turned off and on, respectively, i.e., the off and on images. (c) The lidar signal is obtained by vertically binning the recorded images, subtracting the background signal and performing signal averaging. The pixel-distance relationship is calibrated by measuring the lidar echo from e.g., a tall building with a known distance.

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