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Author(s):
Han, Yu; Salido Monzú, David; Wieser, Andreas

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Delay-Augmented Spectrometry for Target Classification Using a Frequency-Comb LiDAR

Yu Han*, David Salido-Monzú and Andreas Wieser

Institute of Geodesy and Photogrammetry, ETH Zurich, 8093 Zurich, Switzerland
yu.han@geod.baug.ethz.ch

Abstract: We demonstrate LiDAR-based remote spectrometry of natural targets augmented with delay spectra using an ultra-broadband frequency comb. Material-dependent spectrally-resolved delays with an equivalent sensitivity better than 100 μm complement reflectance signatures for enhanced target classification.

1. Introduction

Multispectral LiDAR enables simultaneous acquisition of geometry and material properties over long ranges by combining ToF-based distance measurements with remote spectroscopy. The spectroscopic information can be used to assist segmentation of the collected 3D point cloud data [1] or to estimate relevant material parameters in structural or vegetation health monitoring [2]. Current state-of-the-art multispectral LiDARs are based on supercontinuum sources providing reflectance estimates over some tens of spectral channels and mm-level range resolution [3]. We propose and demonstrate an advanced alternative to multispectral LiDAR using the intermode beat notes of an ultra-broadband frequency comb, that enables distance precision in the sub-mm level and enhanced remote spectroscopy by resolving material-dependent relative delays in addition to reflectance. The spectrally-resolved delays can be interpreted as an apparent distance spectrum. This encodes material information related to the surface condition, and size and concentration of scatterers in the sub-surface layers, which is not fully represented by the reflectance information of established multispectral LiDARs alone. The combination of both signatures offers improved classification potential and prospectively allows accessing additional material parameters. We describe herein the fundamental measurement principle of this approach, and show results obtained using a proof-of-concept experimental implementation. The results show a significant instrumental improvement over our preliminary work [4] and demonstrate the capacity of the proposed method to access dispersive phenomena which augment the standard reflectance estimates for target classification and material probing.

2. Measurement principle and setup

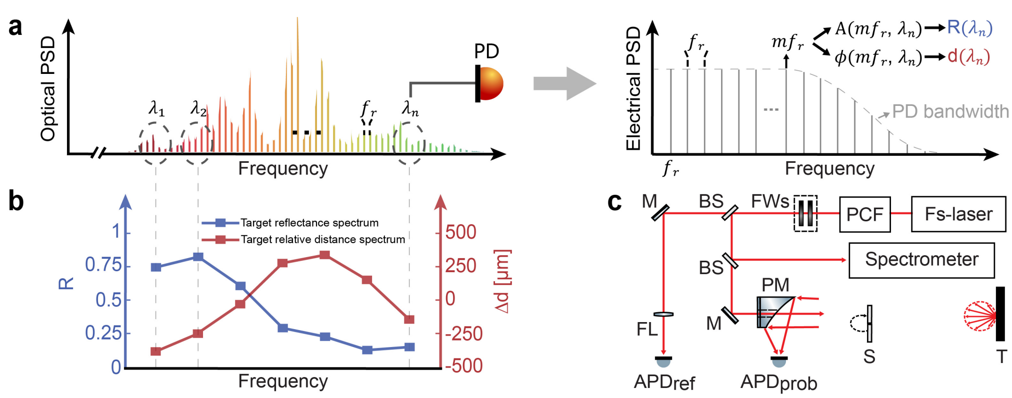

Fig. 1: (a) Optical power spectral density (PSD) of broadened frequency comb and electrical PSD from direct detection of each band-pass-filtered channel. (b) Estimated reflectance and relative distance spectra of a target. (c) Experimental setup diagram (PCF: photonic crystal fiber, FWs: filter wheels, PM: parabolic mirror, APD: avalanche photodiode, S: reflectance standard, T: target).

Direct detection of any spectral channel with center wavelength λ_n of an ultra-broadband optical frequency comb with repetition rate f_r produces a corresponding RF comb on the photodetector (PD) output due to intermode beating (Fig. 1(a)). Given adequate radio- and geometric referencing, the amplitude and phase of the electrical beat notes at an integer multiple m of f_r can be converted into the reflectance and apparent distance of the backscattering target for the corresponding spectral channel. Replicating these observations with time or spatial multiplexing across the available source spectrum allows deriving reflectance and relative distance spectra (Fig. 1(b)). Given the high ranging resolution of this approach on natural targets along with adequate calibration of instrumental systematics, the relative distance spectrum is dominated by the dispersive behaviour of the target, thus producing repeatable material-dependent signatures that complement the reflectance spectrum for better target classification.

Our experimental setup uses a supercontinuum comb (550 nm - 1050 nm) derived from a 780 nm fs-laser coherently broadened in a PCF. Seven 40-nm spectral channels between 600 nm and 900 nm are sequentially filtered before launching towards the target samples 0.5 m away. The backreflected light is focused by a highly achromatic off-axis PM on the probing APD, while part of the original beam is collected on an independent reference ADP for phase referencing and noise reduction. After downconversion and digitization of the APD outputs, phase and power measurements per spectral channel are derived from differential lock-in demodulation on the 900 MHz beat notes integrated over 1 ms. Reflectance and distance spectra are obtained therefrom after normalization with equivalent multiplexed measurements on a flipping 60% diffuse reflectance standard.

3. Results

The short- (2 minutes) and long-term (11 hours) precision of the developed setup was assessed by repeatedly measuring the apparent distance spectrum of a 25% reflectance standard (Fig. 2(a)), shows the empirical standard deviation which is better than 60 μm for all the spectral channels. We then probed five common material specimens (Fig. 2(b)) on ten different positions. The average and range of the obtained distance and reflectance spectra across the ten positions per sample are shown in Figs. 2(c) and (d). The results visually show that both types of signatures can provide large classification separability between targets despite their respective inhomogeneities. Both reflectance spectra (Fig. 2(d)) and relative distance spectra (Fig. 2(c)) show challenging separation cases for different materials (see e.g. specimens 1, 3, and 4). The benefit of complementing the reflectance signatures with distance spectra for enhanced classification is visible on the arbitrarily-selected materials herein, and offers potential for differentiating otherwise challenging targets of similar visual appearance and reflectance.

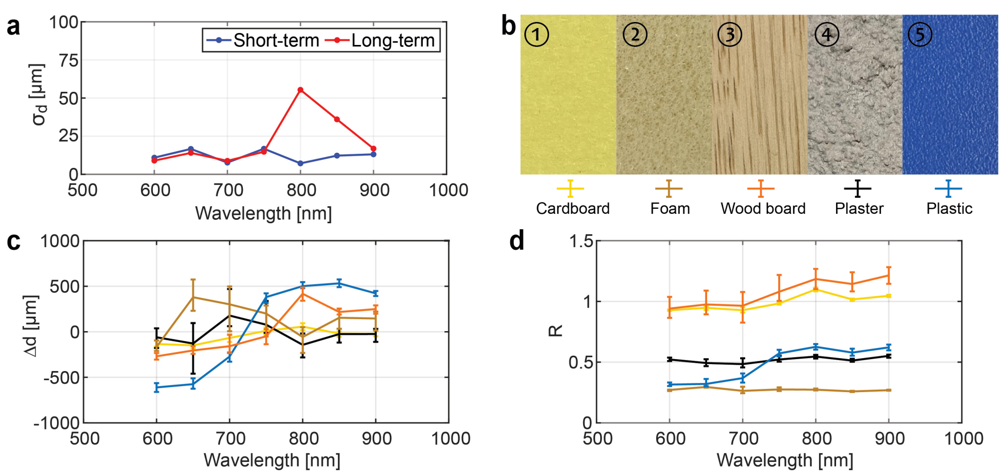

Fig. 2: (a) Short- and long-term distance measurement precision on 25% reflectance standard. (b) Target material specimens. (c) Relative distance spectra and (d) reflectance spectra for the tested materials (mean and range of estimations for ten positions).

4. Conclusion

We propose and demonstrate an ultra-broadband frequency-comb-based LiDAR capable of measuring material-dependent relative delay spectra of natural targets in addition to reflectance spectra. Proof-of-concept results on common materials show the potential of this additional delay signature for enhanced target classification. This approach represents a promising basis towards more comprehensive LiDAR-based environment digitization.

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