Phase-Based Multi-Tone CW Lidar: A Technique for Ranging Beyond the Coherence Length of the CW Laser

Mustafa Mert Bayer, Xun Li, Ataberk Atalar and Ozdal Boyraz
Department of Electrical Engineering and Computer Science, University of California, Irvine, California, USA
Author e-mail address: bayerm@uci.edu, xunl12@uci.edu, aatalar@uci.edu, *and* oboyraz@uci.edu

Abstract: We experimentally demonstrate ranging and velocimetry at >500× beyond the coherence length of a CW laser in a technique called phase-based multi-tone continuous-wave lidar that eliminates the need for any form of phase or frequency sweeping.

1. Introduction

The interest in the cube, micro, and small satellites is rapidly growing to fulfill the requirements of various space missions and applications [1]. Light detection and ranging (lidar) instruments are currently developed and implemented in the spacecraft to realize the desired metrology [2]. The lidars operating in the pulsed mode are opted to perform the ranging, which utilizes the propagation time of the high-peak-power laser pulses that are in flight. Compared to the continuous wave (CW) alternatives, the pulsed lidars have lower ranging resolution due to detection electronics and suffer from a low signal-to-noise ratio (SNR) [3]. Most of the CW lidars operate by sweeping the frequency, amplitude, or phase of a light source and convolving the phase-shifted echo signal with a local oscillator to compute the range of a target. The sweeping and coherence length requirements of the utilized lasers prohibit them to be the primary choice for space or ultra long-distance applications [4].

Here, we present the experimental demonstration of the new Phase-Based Multi-Tone Continuous Wave (PB-MTCW) lidar technique that is suitable for higher resolution single-shot ranging and velocimetry measurements without coherence length limitations. Instead of performing any form of sweeping, PB-MTCW lidar employs static RF modulation frequencies via an electro-optic modulator and compares the phase and frequency variations in between each modulation tone to generate the target distance [5–7]. The new algorithm that mixes the sidebands annihilates the impact of the laser phase noise or any other common noise and hence mitigates the ultra-narrow linewidth requirements for CW lidars [8]. Experimentally, we show that the proposed technique can perform ranging and velocimetry at distances more than 500× (limited by the set up) the coherence length of a laser with 1cm range and 0.5cm/s velocity accuracies. Tone selections can be further improved for a longer range and better resolution.

2. Working Principle

The proposed configuration is illustrated in Fig. 1. First, the CW laser is split into two via a fiber coupler. The unmodulated arm is kept as a local oscillator and the other branch is transmitted into a Mach-Zehnder modulator (MZM). A total of N RF modulation frequencies are fed to the MZM with different frequencies of ω_i. The modulated light is then further modulated via a high extinction-ratio electro-optic modulator (EOM) to realize a quasi-CW pulsation with an optimized repetition rate and duty cycle based on the desired operation. The quasi-CW MTCW pulse is propagated in the free space and the echo signal is collected and transmitted to the photodetector (PD) via a collimator and a circulator, which is further coupled with the local oscillator.

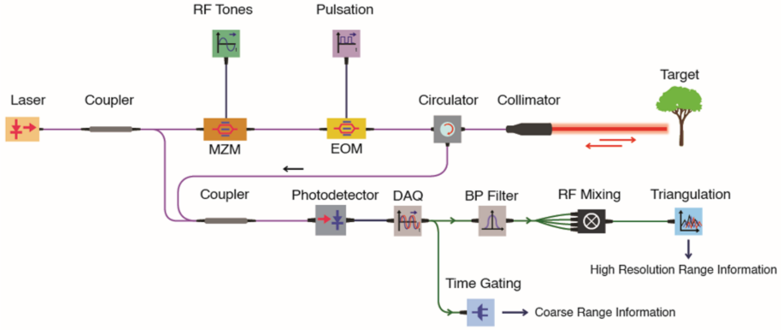

Fig. 1 Schematic of the proposed phase-based multi-tone continuous-wave lidar architecture.

As illustrated in Fig. 1, bandpass filters (which can be analog or digital) near the RF tones are implemented to get the waveform of a single tone. The self-beating terms will diminish to the high scattering losses, while the cross-beating components carry the phase and frequency information of the echo signal. The laser phase noise, optical carrier phase, and frequency-synthesizer phase-noise will be seen as amplitude variations over RF tones. In the new algorithm we have developed we RF mix the resultant modulation tones to generate the noise-free intermediate frequency (IF) component that will have the representation of $A_i A_j \cos\left(\Delta\omega_{i,j} t \pm \Delta\phi_{i,j}\right)$, where $\Delta\phi_{i,j}$, and $\Delta\omega_{i,j}$ are the phase and frequency differences of i^{th} and j^{th} tones ($i \neq j$), respectively. As a result, the target distance can be computed through $L_m = \left(2\pi n + \Delta\phi_{i,j}\right) c / \Delta\omega_{i,j}$, where n is an integer. By using the results generated by multiple tones, it is possible to triangulate the L_m as in [7,8]. The unambiguous range of the system is $L_u = 2\pi c/\omega_{gcd}$, where ω_{gcd} is the greatest common divisor of $\Delta\omega_{i,j}$. The time gating of the quasi-CW pulsation or using a low-frequency phase-locked RF tone will break the limit of L_u by yielding the coarse range information. Then, the triangulation of the final IF phases will determine the actual target distance with a higher resolution.

3. Results and Discussion

To prove the PB-MTCW concept, we prepared a testbench similar to Fig. 1, where the circulator is replaced with a beamsplitter (BS) and a target reflector is placed ~80-120cm away from the output facet of the BS. Two different lasers operating at 1064nm are used with two different linewidths of <100kHz and 5.3GHz that correspond to a coherence length of 1km and 1.8cm, respectively. Two sets of experiments are performed to show the ranging via PB-MTCW lidar with 4 RF modulation tones. First, the target reflector is placed at ~101±0.5cm, where the actual target distance is measured via a measurement tape with ±0.5cm accuracy. We performed ranging by using both lasers consecutively and simulated the PB-MTCW lidar by setting the target distance as 101cm. The measurement and simulation results of the triangulation algorithm are presented in Fig. 2(a). Here, the minimum standard deviation point (σ_{min}) corresponds to the target distance. The measurement with the high coherence laser yields a target distance of 101.2cm, while the low coherence source indicates 101.3cm. The resolution of the PB-MTCW lidar is dictated by the phase resolution, $d\phi_i$, that depends on the sampling rate, jitter, surface roughness under the spot size, etc. It is possible to formalize the minimum theoretical resolution by considering a noise-free case, where $d\phi_i = \omega_i \times dt$ and $\Delta L = c \times dt$, where dt is the time resolution. The final dt becomes ~24ps after digitally interpolating the data and the theoretical minimum resolution is calculated as 0.72cm for this experiment.

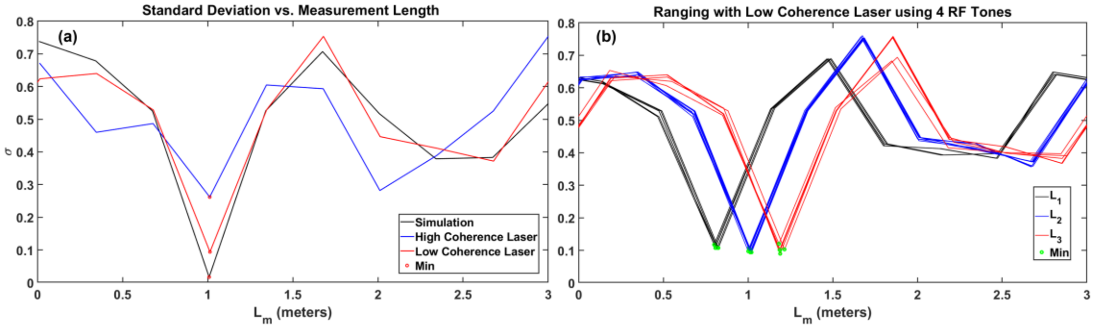

Fig. 2 (a) Experimental triangulation results with high coherence and low coherence laser source along with the simulation results, while the target is placed at ~101cm. (b) Results with low coherence laser at three different target distances of ~82cm, ~102cm, and ~120cm.

In the second experiment, we used only the 5.3GHz linewidth laser to demonstrate the ranging beyond the coherence length of the laser. Here, we moved the target reflector first ~20cm, then ~18cm starting at a stage distance of 82cm up to 120cm, which corresponds to more than 9m path length including the fibers after the MZM. Then, we performed ranging for 10 trials at each location, which we name as L_1, L_2, and L_3, respectively. The ranging results are presented in Fig. 2(b) for all positions. The average measured distances are 82.1cm, 102.4cm, and 120.0cm, respectively. Similarly, the measured path differences are 20.3cm and 17.5cm. The standard deviations of the measurements in 10 trials for three locations are 0.74, 0.67, and 0.98cm, respectively. The <1cm error indicates the measurement resolution.

4. Conclusion

Overall, we demonstrate the PB-MTCW ranging of targets using high coherence and low coherence laser source of a target placed at >500× larger than the coherence length of the laser without employing any form of phase, frequency, or amplitude sweeping. Results from stationary and dynamic targets will be presented in detail.

5. Acknowledgments

This work was supported by the Office of Naval Research under grant number # N00014-18-1-2845.

6. References

1. J. L. Bufton, *et.al.*, "Airborne lidar for profiling of surface topography," Opt. Eng. **30**, 72–79 (1991).
2. R. H. Couch, *et.al.*, " (LITE): NASA's first in-space lidar system for atmospheric research," Opt. Eng. **30**, 88–96 (1991).
3. M.-C. Amann, *et.al.*, "Laser ranging: a critical review of unusual techniques for distance measurement," Opt. Eng. **40**, (2001).
4. B. Behroozpour, *et.al.*, "Lidar system architectures and circuits," IEEE Commun. Mag. **55**, 135–142 (2017).
5. R. Torun, *et.al.*, "Realization of Multitone Continuous Wave Lidar," IEEE Photonics J. **11**, 1–10 (2019).
6. M. M. Bayer, *et.al.*, "Simultaneous ranging and velocimetry with multi-tone continuous wave lidar," Opt. Express **28**, 17241–17252 (2020).
7. M. M. Bayer and O. Boyraz, "Ranging and velocimetry measurements by phase-based MTCW lidar," Opt. Express **29**, 13552–13562 (2021).
8. M. M. Bayer, *et.al.*, "Single-shot ranging and velocimetry with a CW lidar far beyond the coherence length of the CW laser," Opt. Express **29**, 42343–42354 (2021).