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# FMCW LIDAR RANGE AND VELOCITY ESTIMATION BEYOND THE LASER COHERENCE

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## ABSTRACT

Frequency modulated continuous wave (FMCW) LIDAR is a promising technology for high precision 3D sensing applications. However, due to laser phase noise, these systems are usually restricted to target detection below 100 m. In this paper, we present a digital signal processing technique to extend the target range and velocity estimations beyond the laser coherence length. This technique is tested over realistic data from a Monte Carlo model.

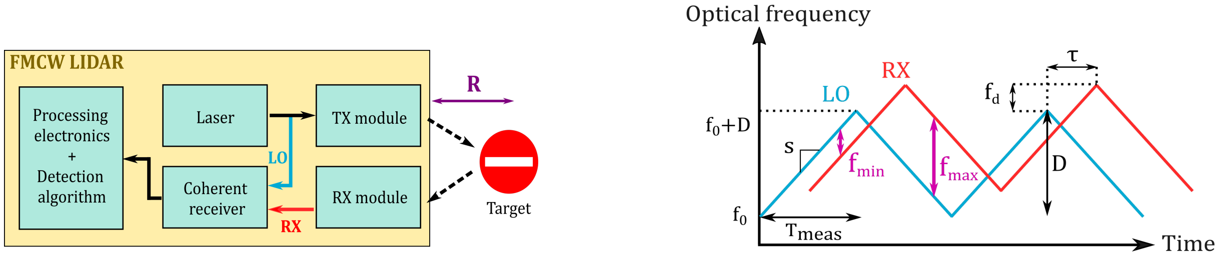
**MOTS-CLEFS :** *LIDAR; laser linewidth; estimation; precision*

## 1. INTRODUCTION

High precision 3D sensing systems as Frequency Modulated Continuous Wave (FMCW) LIDARS are gaining interest for automotive, robotic and medical applications. FMCW LIDAR is based on coherent detection and shows high resolution and instantaneous radial velocity information [1]. However, the laser phase noise strongly impacts the received signal spectrum, which spreads from a narrow squared Cardinal Sine to a Lorentzian function for targets beyond the laser coherence length, $L_c$, making it uncertain the range and velocity estimations. Embedded digital signal processing (DSP) is a promising approach to extend LIDAR detection range beyond $L_c$ [2]. In this article, we further evaluate the Least Square Estimation (LSE)-based algorithm suitability for the estimation of velocity beyond $L_c$.

## 2. FMCW LIDAR PRINCIPLE

The considered FMCW LIDAR is presented on Fig. 1a. The laser optical frequency is modulated with a triangular waveform Fig. 1b to enable target range and velocity estimation. During the measurement period $T_{meas}$, the laser frequency is chirped with a slope $s = D/T_{meas}$, where $D$ is the frequency excursion. The FMCW signal hits a target and is backscattered to the coherent receiver (RX module) with a delay $\tau$ where it mixes with the reference local oscillator (LO).



(a) (b)

Figure 1: (a) FMCW LIDAR system. (b) FMCW transmitted (blue) and reflected (red) waveforms

Target range, $R$ and velocity, $V$ are retrieved from the minimum, $f_{min}$ and maximum, $f_{max}$ detected beat frequencies, which are estimated after Fourier Transform (FT) of the photodetected signal, as:

$$R = \frac{c}{4s}(f_{max} + f_{min}) \quad \text{and} \quad V = \frac{\lambda}{4}(f_{max} - f_{min}) \tag{1}$$

where $c$ is the light velocity in vacuum and $\lambda$ is the laser wavelength.

## 3. RANGE AND VELOCITY ESTIMATION BEYOND THE LASER COHERENCE LENGTH

The laser phase noise is modeled as a flat frequency noise with power spectrum density $S_{\nu_n}(f)$ depending on the laser linewidth $\Delta\nu$ (2). Frequency noise samples are integrated in time to express laser phase noise contributions $\Phi_n$ of the direct and reflected paths into the photodetected beat current, $I_b$ with beat frequency $f_b$=$f_{min}$ or $f_{max}$ as expressed in (2). The periodogram (PER) of $I_b$ is evaluated over $T_{meas}$. An LSE algorithm is used to search the expected Lorentzian shape over the PER of $I_b$ and estimates $f_{min}$ and $f_{max}$ to derive $R$ and $V$ (1). Tab. 1 details the system specifications, where the target is located beyond $L_c$.

$$S_{\nu_n}(f)=\frac{\Delta\nu}{2\pi} \quad , \quad \Phi_n=\int_t 2\pi\Delta\nu dt \quad \text{and} \quad I_b=cos(2\pi f_b t+\Phi_n(t)-\Phi_n(t-\tau)) \tag{2}$$

| Parameter | Value |
|---|---|
| LIDAR output power | 10 mW |
| Laser linewidth | 1 MHz |
| Measurement time $T_{meas}$ | 10 $\mu$s |
| Frequency excursion $D$ | 1 GHz |
| Attenuation coeff in air $\alpha$ | 0.43 dB/km |
| Target range $R$ | 150 m |
| Target velocity $V$ | 60 km/h |
| Target reflectivity | 10% |
| Receiver aperture size | 1 cm$^2$ |
| Detector responsivity | 0.8 A/W |
| Detector bandwidth | 500 MHz |
| Estimation algorithm | LLSE |

Table 1: System specifications

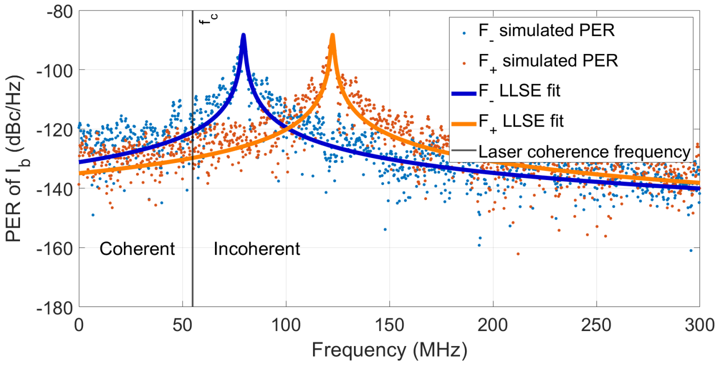


Figure 2: Periodogram of the photocurrent with LLSE fitting

## 4. SIMULATION RESULTS AND DISCUSSION

As it can be seen from Fig. 2, the Lorentzian LSE (LLSE) algorithm accurately fits the simulated PSDs for a target located at 150 m, i.e. beyond the laser coherent length $L_c$ = 82 m (corresponding to the detected "coherence frequency" $f_c$=55 MHz on Fig. 2). From LLSE, estimated $f_-$ and $f_+$ are 78.7665 MHz and 121.775 MHz respectively, which corresponds to a target range and velocity of 150.406 m and 59.997 km/h respectively. These results are in good agreement with the expected values of 150 m and 60 km/h (Tab. 1). However, for higher velocity targets, $f_-$ approaches zero, making it difficult LLSE fitting.

## CONCLUSION

In this paper, a LSE-based digital signal processing technique is used for target range and velocity estimations beyond the laser coherence length. A Monte Carlo model for the FMCW LIDAR, including the laser phase noise, is introduced to provide realistic data to test the proposed signal processing technique. First simulation results confirm that the target range and velocity are accurately estimated for a target distance larger than $L_c$. LSE can be applied to any laser lineshape, providing that it is known for LSE detection. Future work will be conducted to evaluate the accuracy of LSE-based range and velocity estimations, considering a wide set of scenarios.

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