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Influence Factor Analysis for 3D Imaging Laser Radar Range Profile

[1]*Zhao Yan*, [2]*M.R. Anjum and* [1]*Wang Xiaowei*

[1]School of Optoelectronics, Beijing Institute of Technology, Beijing, China
[2]School of information and Electronic Engineering,
Beijing Institute of Technology, Beijing, China

Abstract: Systematic simulation is an indispensable step in imaging laser radar for the research of system design. Simulated results help to radar designer for choosing the best optimized design method and it provides the foundation for the design of radar data-processing algorithm. This research work proposed a simulated model for the performance of a 3D imaging laser radar using matlab. This simulated model design used laser pulse characters, target characters, media effects such as diffraction propagation and atmospheric turbulence, speckle noise together with the background noise into account to derive the signal waveform from the target. Finally a suitable detection method is needed to estimate the target range profile. Different imaging results are generated by adjusting different parameters values during different operating conditions also some series of simulation results are presented to analyze the range profile influence factors.

Key words: Ladar · Range profile · Target detection · Matlab

INTRODUCTION

3D imaging laser radar can be used to perform non-cooperative target's detection, classification, tracking and for precision guidance. This may be developed for civilian application such as urban planning [1, 2]. This paper will focus on the simulated model of laser radar. Which can predict as close to the real scene, so an important part of radar systematic simulation is the spatial effects that occur on laser beam propagates toward target and then back to the radar receiver. The purpose of this simulated model is to produce a range imaging results. To determine and analyze the 3D laser radar range profile's influencing factors and generates training data for algorithm development.

This research work is organized as follows. In section 2 briefly describes the laser radar model with related work and discussion. The theoretical analysis and simulation result are presented in section 3. The conclusions are drawn in section4.

MATERIALS AND METHODS

Various types of radar system take advantage of different signal propagation process, the description of the process can be decompose into fragments that quantify the effects of various elements of the process. This research work describes direct-detection method, as a coherent detection system. Furthermore, the mixing efficiency in coherent system of signal field with local-oscillator must be considered for signal processing.

Laser Transmitter Model: The laser is defined by the parameters such as wavelength, pulse shape, power etc. The laser transmitter fires a pulse of laser energy it exists for a short time of period, which can be described as Gaussian shape both in its temporal and spatial components [3]. It is quite important to convert intensity of light beam into uniform distribution in practice application of laser to obtain higher lighting performance. It is most prominent that when multiple surfaces are illuminated by laser in non-scanning imaging radar system. In our model we require a discrete form of the signals which is accomplished by sampling the pulse shape both in time and in space, so the temporal and spatial resolution can be dynamically set according to the sampling criteria [4].

Target Reflection Model: An important parameter in target model is the reflectivity of the target surface, this parameter is a unit less quantity that captures the ability of the material to reflect laser radiation and its typical value range from 0.02 to 0.25. Other parameters like range, shape and surface area should be adjusted. In order to

Corresponding Author: Zhao Yan, School of Optoelectronics, Beijing Institute of Technology, Beijing, China.

simplify simulation work, we present three assumptions. First, the target area is smaller than the laser irradiation area at the target plane and the target can be detected completely by the detector. Second, the target surface is lambertian surface, so the dispersion solid angle takes on the value of π. Finally, the target surface is perpendicular to the direction of light propagation.

Receiver Model: The parameters in this model include field of view, receiving aperture of optics, efficiency, detecting resolution of pixels, etc. The efficiency of the laser radar receiver is driven by both the optics transmission and the quantum efficiency of the detector. In order to model multiple target with different ranges, shapes and surface reflectivity's imaging. We introduce the concept of the target profile [5]. The target range profile takes the place of the target variable times the surface reflectivity and the two parameters are removed from general range equation, so the returned signal power can be calculated that has an area of $1m^2$ with a unity reflectance. The convolution of the returned signal power and the target range profile is the total returned of signal power.

Atmosphere Transmission: Atmosphere transmission keep the light deviate from the straightway. In this section, we will discuss the diffraction effects of light propagation through atmosphere and optical system as well as the effects of atmospheric turbulence. Account for these spatial effects will improve the fidelity of laser radar model.

The general solution of light wave diffraction propagation problem, which is known as Rayleigh Sommerfeld diffraction integral method [6]. The field g at source plane is propagated to a distant plane, the field f at the distant plane can be written as:

$$f(w_p,s_q,t) \approx \sum_{m=1}^{N}\sum_{n=1}^{N}\frac{g(x_m,y_n)ze^{j2\pi v[t-R(x_m,y_n,w_p,s_q)/c]}}{j\lambda R^2(x_m,y_n,w_p,s_q)} \tag{2.1}$$

In this equation, R is the range from a point (x_m,y_n) in the source plane to a point (w_p,s_q) in the distant plane, z is the distant between the planes.

The size of entrance pupil or shot pupil of the receiver optical system is limited, which elicits diffraction limited imaging. It means only lower frequency component of light can go into the entrance pupil, obviously the performance of optic is limited by this diffraction effect. A point source at the target location is propagated to receiver aperture, then it modified by the focusing optics and propagated to the detector plane, we can calculate the intensity distribution. This intensity distribution is the point spread function of the diffraction system.

The atmosphere's reflective index randomly evolves over time and space, this effect causes light to be randomly distorted as it propagates [7, 8]. The effect derived from atmospheric turbulence at one moment. We care about the effects caused by clean air that the reflective index changes gently rather than turbid air such as dense fog. In addition, we assume that the wavelength locate at atmospheric window region so that we ignore the atmospheric absorption.

For imaging through the uneven atmosphere and radar receiver optic system, we can apply linear system theory and use transfer function to express imaging character. The parameter r_0 is a common used parameter when involve atmospheric turbulence transfer function, it also known as the Fried parameter because it was first introduced by Fried [9]. Where r_0 and consider it as a part of calculating the average transfer function of atmosphere turbulence. We can easily understand that our radar receiver optics imaging is short exposure imagery, so here we give Fried's average short exposure transfer function:

$$H_{atm}(f_x,f_y) = e^{-3.44[\frac{\lambda^2 f_l^2(f_x^2+f_y^2)}{r_0^2}]^{5/6}\{1-[\frac{\lambda^2 f_l^2(f_x^2+f_y^2)}{D_r^2}]^{1/6}\}} \tag{2.2}$$

In this equation, f_l is the focal length of the receiver optic system, D_r is the receiving aperture of receiver optic system.

Source of Noise: Many phenomenon's contributes noise to direct detection radar system, we discuss two main sources of noise in our simulation such as laser speckle noise and background noise. Laser speckle noise is caused by interference occurring at detection plane from a large collection of independent radiators because of the laser coherence and the surface roughness of the material. Goodman gives a full treatment of the mathematics that speckle can be simulated by modeling the number of detected photos as a negative binomial random, but account for the rate of computation, we model that as a Possionian random instead when we discuss other influence factors rather than noise. The background noise constitutes other signal collected by detector that does not come from the laser transmitter. It follows Poissonian distribution as well [10].

RESULTS AND DISCUSSION

A direct-detection radar system simulations result has obtained by using Matlab, a commercial data-analysis and visualization tool. Users can choose all modules variable to simulate the radar system performance with different conditions through the GUI. In this section we will present some series of simulations while one parameter at a time is changed. Table 1 identifies the known specifications for the system.

Different Atmospheric Conditions: As above discussed, the parameter r_0 is a common used parameter that describe atmospheric turbulence effects. The greater value of r_0 is, the better atmospheric condition becomes. In Figure 1 for instance, the three-bar target has a background at distance is 0.6m from the three separate raised surfaces, the seeing parameter r_0 is changed. Other parameters used in simulation are listed in Table 1. Where for example the detector array size is 50 multiple of 50, the receiver focal length is 1m. We can see the range profile with noise as Fig. 1 shows, when r_0 parameter equals to 0.02m and 0.2m.

Different Receiver Optics: For this diffraction-limited receiver optics system with aperture equals to D_r, the transfer function is:

$$H(f_x, f_y) = circ(\frac{\sqrt{f_x^2 + f_y^2}}{D_r / 2\lambda f_l}) \quad (3.1)$$

So the diffraction-limited cutoff frequency is:

$$f_0 = \frac{D_r}{2 f_l \lambda} \quad (3.2)$$

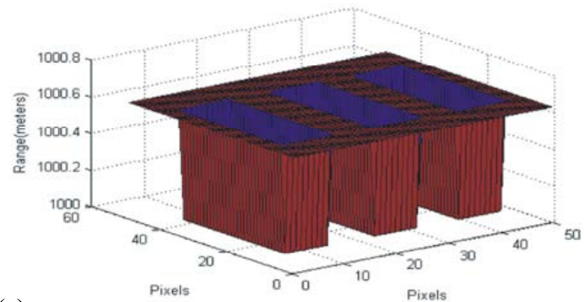
where D_r is the receiver optics aperture, f_l is the focal length of the receiver optics. The larger cutoff frequency is, the more frequency spectrum component of light can enter the receiver optics, so we can obtain the better imaging quality. In this section other parameters remain the same, the target is also a three-bar target as Fig. 1(a) shows, we only change the receiver optics parameters, the optics aperture and focal length. The range profile in these circumstances as Fig. 2 shows.

But the value of optics aperture or focal length cannot be an arbitrary number, because to ensure Nyquist sampling, the pixel size in the detector array must abide by the following relationship:

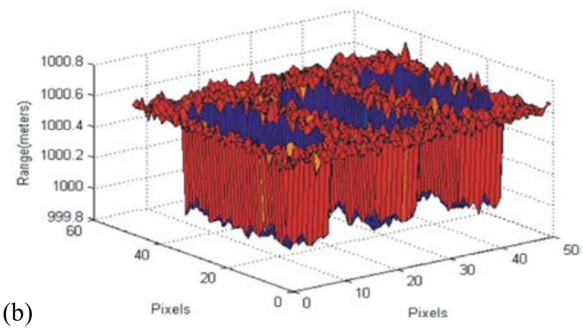
$$\text{Max pixel size} = \frac{\lambda f_l}{D_r} \quad (3.3)$$

Table 1: 3D non-scanning imaging radar system specifications

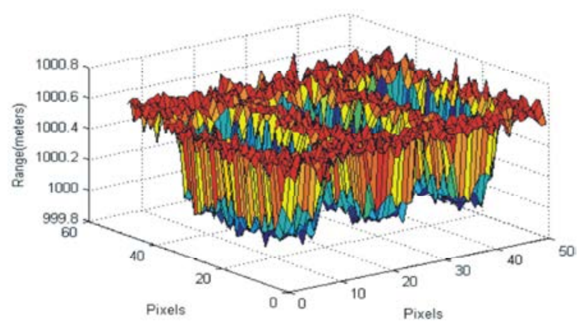
No.	Known System parameters	Defined Value
1	Laser wavelength	1.55um
2	Pulse energy	1mJ
3	Receiver bandwidth	0.001um
4	Detector array size	50*50
5	Pixel size	10um
6	Receiver aperture	0.0775m
7	Receiver focal length	1m
8	Atmospheric seeing	0.2m



(a)



(b)



(c)

Fig. 1: (a) The three separate raised surfaces are located at 1000m and the background is located at 1000.6m. (b) and (c) The target range profile when r_0 is changed, to the top r_0=0.2m and to the bottom r_0=0.02m

For a certain value of the pixel size in the detector array, the value of optics aperture or focal length is under restrictions.

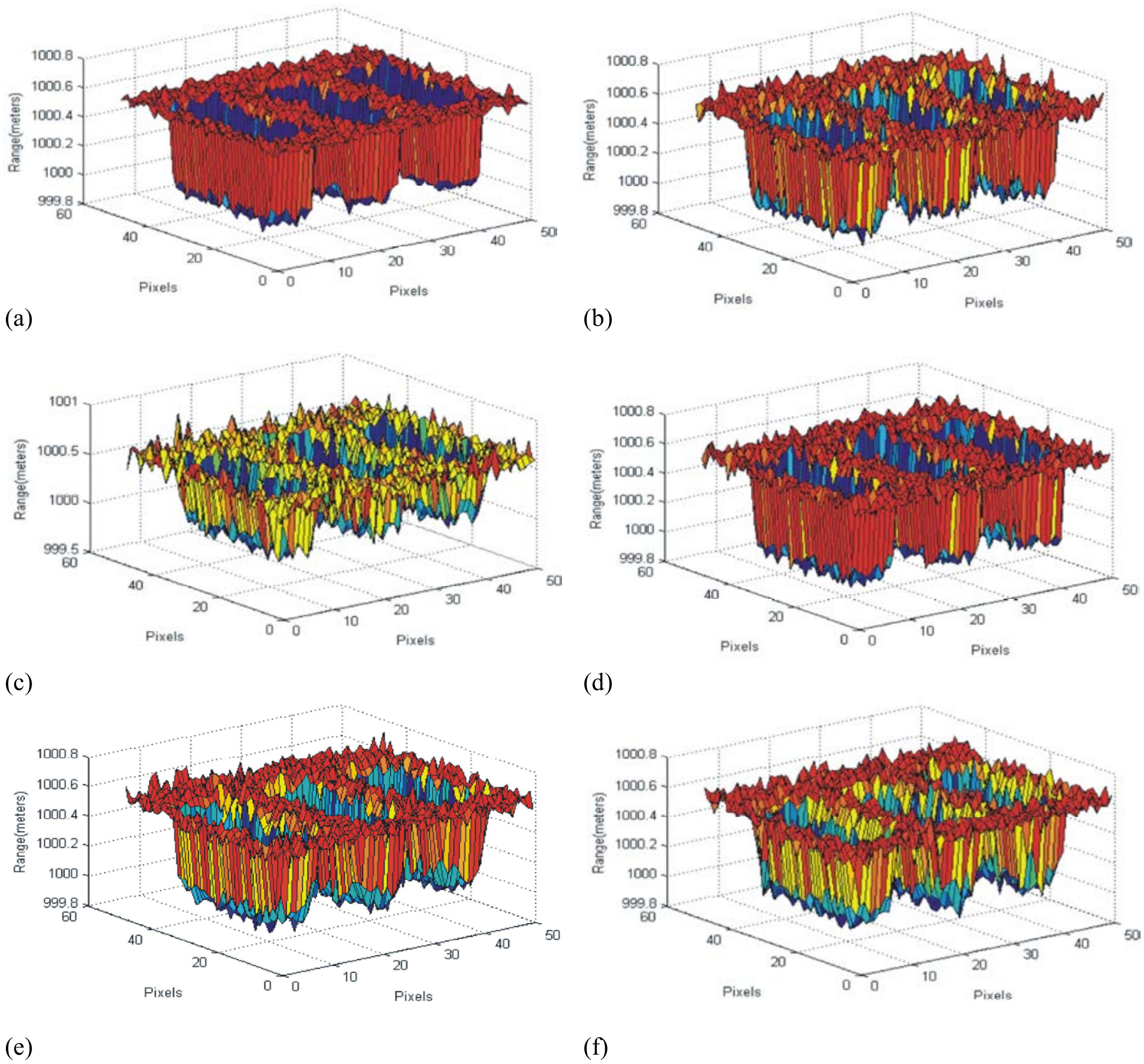


Fig. 2: (a) (b) and (c) The target range profile when f_l equals to 1m and D_r equals to 0.1m, 0.07m and 0.05m from top to bottom. (d) (e) and (f) The target range profile when D_r equals to 0.0775m and f_l equals to 1m, 1.2m and 1.5m from top to bottom

Different Target Shapes: The field of view of receiver contains multiple surfaces with different ranges, in this case, the laser echo pulse contains a response from different surfaces. One situation may arise that the three-bar target has different distances to the background, when the distance is large enough then the reflection gives a distinct double pulse responses. We compare the imaging results that the target has a background at distance is 0.6m and 0.9m from the three separate raised surfaces as in Figure 3. Shows, Here we adjust the focal length of the receiver optics to 1.5m and r_0 parameter to 0.05 m.

Then the target is modified as shown in Figure 4. The corresponding results we can see in Fig. 5.

Different Noise Effects: Firstly is the laser speckle noise that is a negative binomial random variable with a mean equal to photon number detected by detector and a variance which relate to the number of degrees of freedom of the light. The number of degrees of freedom of the light is a measure of the coherence of the light both spatially and temporally. For fully coherent light it equals to 1 and for fully incoherent light it approaches to infinity. To simulate the speckle effects in this section,

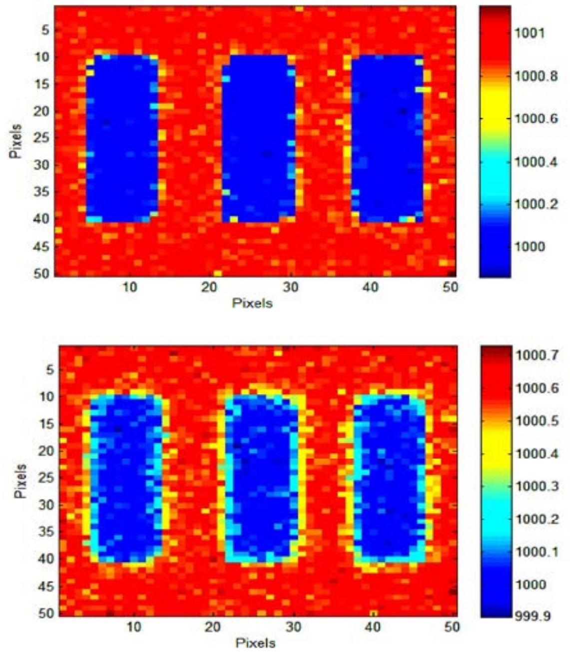


Fig. 3: The target range profile with three separate raised surfaces located at 1000m and the background located at different distance. To the top the distance is 1000.9m and to the bottom that is 1000.6m

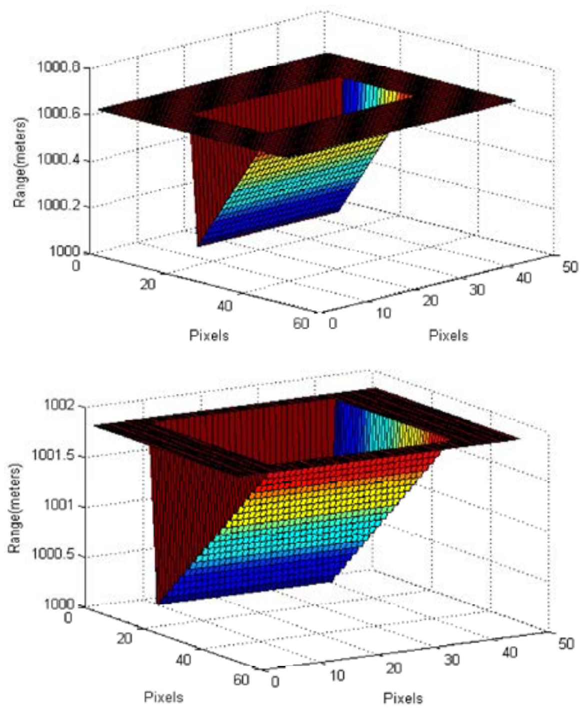


Fig. 4: The titled target with different range depth, to the top the range depth is 0.6m and to the bottom that is 1.8m

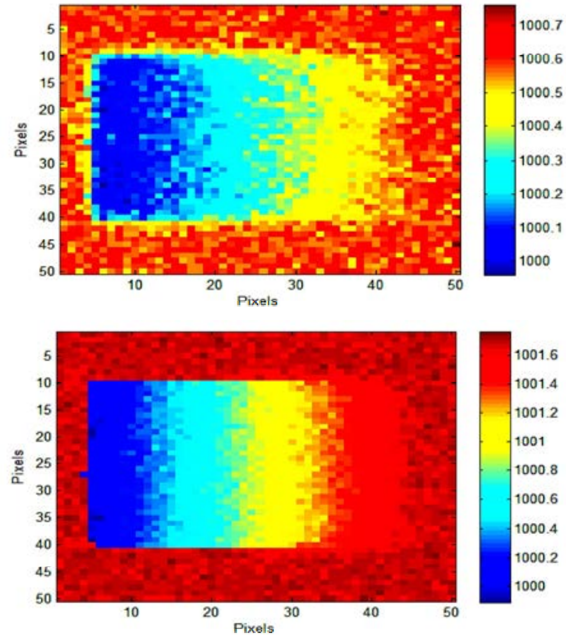


Fig. 5: The range profile produced by a titled target with a range depth of 0.6m and 1.8m relatively

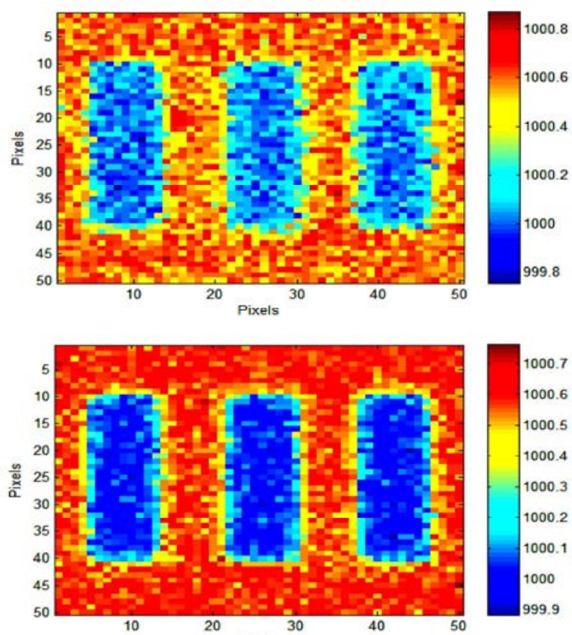


Fig. 6: The target range profile with different speckle noise effects. To the top the number of degrees of freedom of the laser is 1, to the bottom that is 10

all parameters are set as Table 1 and the number of degrees of freedom of the light is changed. We can see the different speckle noise characteristic in Fig. 6.

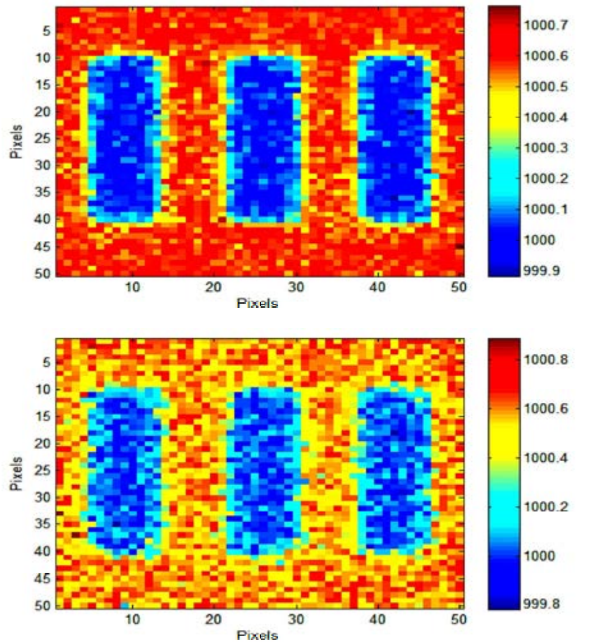


Fig. 7: The target range profile with different background noise effects where the background noise in top picture is greater than that in bottom picture

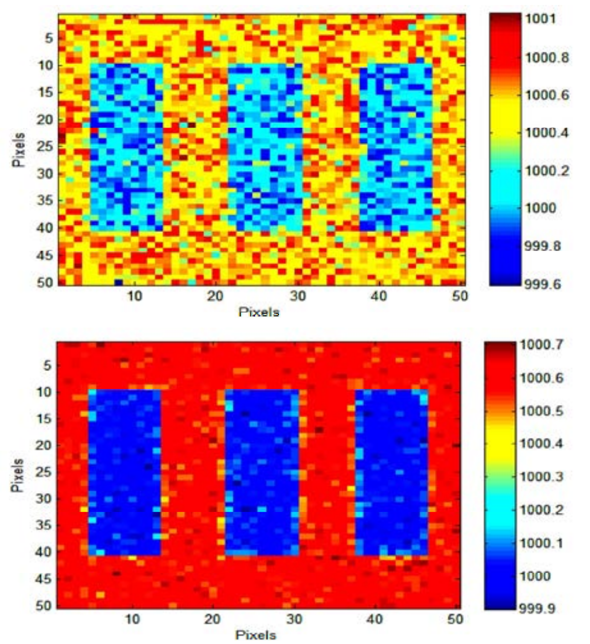


Fig. 8: The target range profile detected with peak detection and cross-correlation detection relatively

The intensity of the background noise will affect the range profile imaging results as well this effect can be illustrated in Figure 7.

Different Detection Algorithms: Many methods for estimating the range to the target had been explored. The peak detection and cross-correlation detection is shown in Fig. 8.

CONCLUSIONS

This paper has discussed the development and use of simulation tool of 3D non-scanning imaging laser radar. We have design a model to represent imaging results of the target. The presented model provides the possibility to acquire best laser radar in practical application. Simulation results have been carried out to verify the effectiveness of the proposed method. This research work would be helpful to the engineering application of imaging laser radar.

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