Influence of Atmospheric Aerosol Backscattering on Incoherent Frequency Modulation Continuous-wave Laser Ranging in the Fog

Yabo Duan, Chengtian Song

***Abstract*—Atmospheric aerosol backscattering is a main factor that affects the ranging accuracy of laser ranging in the fog. The influence on a target-reflected signal in incoherent frequency modulation continuous-wave (FMCW) laser ranging system, which has not yet been well addressed, has been theoretically and experimentally studied in this paper. In order to accurately analyze the signal-to-noise ratio (SNR) of an echo signal in backscattering environment, a quantitative calculation model based on Mie theory is presented. To confirm the validity of this model, a FMCW laser ranging prototype with small size, low power consumption and high ranging accuracy was designed. The laser ranging experiment considered a wide range of the affecting parameters. Experimental results confirm that the calculated SNR of the echo signal based on the quantitative calculation model is identical to the experiment results within acceptable error. Therefore, the quantitative calculation model coupled with the prototype provides an effective way to study the influence of aerosol backscattering on laser ranging in the fog.**

***Index Terms*—frequency modulation continuous-wave (FMCW), laser ranging, backscattering, aerosols**

I. Introduction

Noncontact high-resolution laser ranging is a cost-effective technique that has played a significant role in both military and civilian fields in recent decades [1]-[3]. Incoherent frequency modulation continuous-wave (FMCW) laser ranging is a well-known active ranging method that offers high precision [4]. The method measures target distances by calculating the frequency of a beat signal that is the result of mixing a local oscillator signal with the echo signal.

Atmospheric aerosol is the general term used to describe solid and liquid particles suspended in the atmosphere. During the collection of an echo signal, disturbances that are a result of aerosol backscattering always accompany the echo signal. Therefore, aerosol backscattering is regarded as a main factor that affects the target echo signal reception in fog, snow and rain. Atmospheric aerosol backscattering is also a main reason of energy loss when the laser transmits through clouds and smoke [5]. The influence of atmospheric aerosol backscattering on the waveform of a target-reflected signal has been well addressed through theoretically studied [6] where the expression of backscattering signal was calculated based on one-particle backscattering model and the Mie theory. Walkerr studied the influence of aerosols on marine atmospheric surface layer optics [7]. Mandrosov discussed the influence of turbulent atmosphere on the Fourier telescopy image [8]. Evan et al did research on backscattering signatures of the biological aerosols in infrared [9]. Li et al analyzed the backscattering characteristics of objects for remote laser voice acquisition [10]. High frequency continuous wave modulation techniques have been applied to suppress the backscattering influence [11]-[13]. David et al indicated that the FMCW ranging technique can detect both the desired object and the volumetric center of the backscattering clutter signal [14]. In aforementioned articles, there is no detailed analysis of the relationship between aerosol backscattering and its influence on the performance of FMCW laser ranging. This paper introduces a quantitative calculation model for analyzing the influence of aerosol backscattering on a target-reflected signal in the fog. Numerical simulations and the experiment of FMCW laser ranging system are performed to evaluate the effectiveness of the proposed method.

The remainder of this paper is outlined as follows. The principle of the FMCW laser ranging system is reviewed briefly in Section II; Influence of aerosol backscattering on a laser signal is discussed, and a quantitative calculation model is proposed in Section III, while in Section IV, experimental setups and procedures are presented. Consequently, the analysis of experimental results is illustrated in Section V. Finally, conclusions are drawn in Section VI.

II. FMCW Laser Ranging Technique

A FMCW laser ranging system has been designed that operates with a static and cooperative target for distance from 1m to 15m. Fig. 1 is the simple framework of the FMCW laser ranging system. The output of a direct digital synthesizer (DDS) is used to modulate the custom laser source. The output laser beam is split into two parts. One part is transmitted to a mixer as the local oscillator (LO) signal. The other part is transmitted to the target. The target-reflected signal is converted to electric current using an avalanche photo diode (APD) at the receiving end. After that, the photoelectric current from APD is mixed with the LO signal through the Mixer to obtain a beat signal. The mixer output is

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Yabo Duan is with Beijing Institute of Technology, Beijing, 100081, China. (e-mail: dybbit@gmail.com).

Chengtian Song is with Beijing Institute of Technology, Beijing, 100081, China. (phone: 010-68914840; fax:010-68914840; e-mail: songct@bit.edu.cn).

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then low-pass filtered to remove some high frequency noise accompanied with the beat signal. In the subsequent process, a Signal Processing module is used to calculate the frequency spectrum of the beat signal through Fast Fourier Transform (FFT) IPCord in FPGA. Finally, we get the target distance.

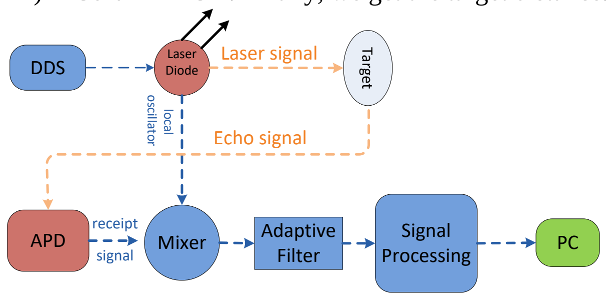


Fig. 1. FMCW laser ranging system

The classic FMCW laser range formula is expressed as follows [13]:

$$R = \frac{vTf_b}{2\Delta f} \tag{1}$$

where R is the target distance. v is the laser transmission speed in air. T is the chirp duration. f_b is the frequency of the beat signal and Δf is the chirp bandwidth. Equation (1) indicates that the measurement precision of f_b will impact the ranging accuracy.

III. Influence of Aerosol Backscattering on Laser Signal

A. *Frequency spectrum analysis of echo signal*

Backscattering is the largest concern in laser ranging application that occurs when the photons reflect off particulates suspended in the atmosphere and arrive at the APD without ever reaching the target. Backscattering signals thus contain no information related to the target, and result in lower resolution and accuracy in laser ranging applications. In this paper, it is assumed that the target is static. Therefore, the Doppler-effect can be ignored. The transmitted laser signal is modulated using a linear frequency-modulated signal as follows.

$$x_e(t) = A\cos(2\pi f_0 t + \frac{\pi B}{T} t^2) \tag{2}$$

where A is the chirp amplitude. f_0 is the minimum frequency in the chirp. B is the modulation bandwidth, and T is the modulation period. The transmitted signal will be reflected when transmitted through both the target and the backscattering "clutter". Thus the echo signal contains both the target echo signal and the backscattering signal. In the ideal case, the echo signal is simply a scaled, delayed version of the transmitted signal without considering the transmission channel interference. Practically, the channel may alter the shape of the echo signal, so the received signal should be considered as the product of a frequency-dependent amplitude function with a delayed version of the transmitted signal, as follows.

$$x_R(t) = i_{ob}(t)x_e(t - t_{0b}) + i_{bk}(t)x_e(t - t_{bk}) \tag{3}$$

where $i_{ob}(t)$ and $i_{bk}(t)$ denote the amplitude of the target echo photocurrent and the backscattering photocurrent, respectively. t_{0b} is the delay introduced by target-reflection and t_{bk} is the delay introduced by the backscattering. The beat signal can also be expressed as follows.

$$f_{beat}(t) = i_{ob}(t)\cos(w_{ob}t + \varphi_{ob}) + i_{bk}(t)\cos(w_{bk}t + \varphi_{bk}) \tag{4}$$

$$w_{ob} = 2\pi * \frac{B}{T} t_{ob}, w_{bk} = 2\pi * \frac{B}{T} t_{bk}, \tag{5}$$

$$\varphi_{ob} = 2\pi(f_0 t_{ob} - \frac{B}{2T} t^2{}_{ob}), \varphi_{bk} = 2\pi(f_0 t_{bk} - \frac{B}{2T} t^2{}_{bk})$$

F_{beat} is the frequency spectrum of the beat signal as follows.

$$F_{beat} = FFT(f_{beat}(t))$$

$$= \frac{1}{4}[e^{-j\varphi_{ob}} I_{ob}(f + f_{ob}) + e^{-j\varphi_{ob}} I_{ob}(f - f_{ob})]$$

$$+ \frac{1}{4}[e^{-j\varphi_{bk}} I_{bk}(f + f_{bk}) + e^{-j\varphi_{bk}} I_{bk}(f - f_{bk})] \tag{6}$$

where $I_{ob}(f)$ and $I_{bk}(f)$ denote the FFT result of the echo signal amplitudes and backscattering signal amplitudes respectively. Note that the signal in (6) contains two frequency components where f_{ob} defines the beat frequency resulting from the target and f_{bk} defines the beat frequency resulting from the backscattering. In this paper, the frequency point f_{ob} of the echo signal at which the maximum amplitude occurs is detected via FFT calculation. If the amplitude of f_{bk} is closed to the amplitude of f_{ob}, the detection of f_{ob} becomes difficult. Therefore, the backscattering signal included in the echo signal will be a main factor affecting the ranging accuracy.

B. *Quantitative calculation model for backscattering signal*

The driving current of the transmitted signal is defined as follows:

$$I_{tr}(t) = I_{dir} + I_{alt} \sin\Phi \tag{7}$$

where I_{dir} is the DC bias current that is necessary to light the laser diode and I_{alt} is the amplitude of the alternating current. Φ is the instantaneous phase of the chirp current as follows.

$$\Phi = 2\pi(f_0 t + \frac{f_1 - f_0}{2T})t^2 \tag{8}$$

where f_0 is the minimum frequency of the chirp. f_1 is the maximum frequency and T is the modulation period of the chirp signal. The transmitted signal is intensity-modulated as shown below [14].

$$P_{tr}(t) = \frac{\alpha I_{tr}(t)}{A_{area}} = \frac{\alpha(I_{dir} + I_{alt}\sin\Phi)}{A_{area}} \tag{9}$$

where α is a ratio of the transmitted laser power to the driving current, and A_{area} is the laser emitting area in the laser diode.

There are two kinds of attenuation caused by aerosols: absorption and scattering. A quite effective model based on Beer-Bouguer law for calculating the transmission attenuation is presented [15]-[16]. Based on the model, the laser power attenuation can be expressed as follows:

$$P_{re}(t)=\frac{P_{tr}}{z^2}e^{-u(\gamma)z} \tag{10}$$

where P_{re} is the output intensity that transmits along a distance of z in aerosols. P_{tr} is the incidence intensity, and $u(\gamma)$ is the atmospheric extinction coefficient, approximately equals to the scattering coefficient that can be calculated using Mie theory as follows.

$$u(\lambda)=\alpha(\lambda)+\beta(\lambda) \tag{11}$$

Based on (11), $\alpha(\lambda)$ is the absorption coefficient and $\beta(\lambda)$ is the scattering coefficient. The absorption effect can be ignored in this experiment because the backscattering signal is the main factor affecting the ranging accuracy. The scattering coefficient can be expressed as a function of the visibility and wavelength of the laser (λ) using the following formula [17].

$$u(\lambda)=\beta(\lambda)=\frac{3.912}{R_m}\left(\frac{0.55}{\lambda}\right)^q \tag{12}$$

where *Rm* (*km*) is the fog visibility and *q* is the size distribution of scattering particles. q is modified in (13) when the fog visibility is lower than 6 km. In Fig. 2 the relation between the fog visibility and the scattering coefficient is presented.

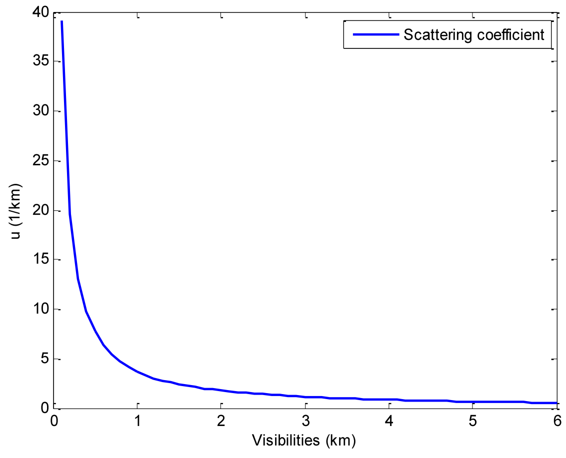


Fig. 2. Simulation curve of scattering coefficient as a function of fog visibility

$$q=\begin{cases}0.34+0.16R_m & 1km<R_m<6km\\ R_m-0.5 & 0.5km<R_m\le 1km\\ 0 & R_m\le 0.5km\end{cases} \tag{13}$$

In the following, we establish a model to analyze the influence of aerosol backscattering on the target-reflected signal in the fog in Fig. 3.

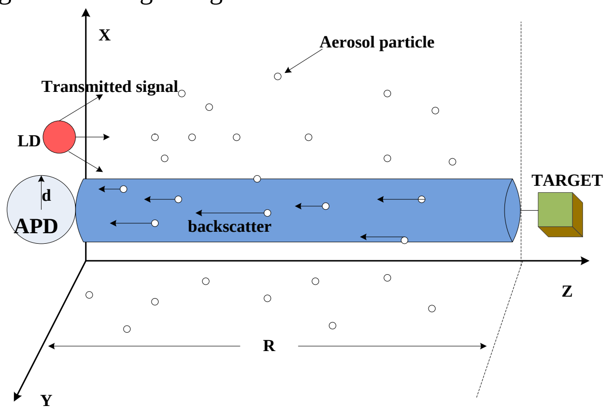


Fig. 3. Calculation model for the backscattering signal

It is assumed that the APD photosensitive surface is a circle with radius d. The distance between the APD and the target is R that equals to the length of the cylinder. The cylinder covers the transmission path of all aerosol particles from APD to the target. Therefore, the backscattering signal produced in the cylinder is collected by a lens that focuses the light power on the APD. The number of particles inside the cylinder is related to the particle distribution function (the number of particles per unit volume (cm^{-3}) per unit with the increment of radius (um)). The particle is lognormal distribution as follows [18].

$$n(r)=\frac{a_l}{2\sqrt{2\pi}}(r\ln\sigma)^{-1}\exp\left\{-\left[\frac{\ln(r/r_g)}{2\ln\sigma}\right]^2\right\} \tag{14}$$

where r is the radius of particles. σ is the standard deviation. r_g is the average radius of the particles and a_l is distribution coefficient. The movement of aerosol particles could be negligible in a short period *T*. The number of aerosol particles in unit volume is defined as follows.

$$X_{\Delta V}=\int_{r_{\min}}^{r_{\max}}n(r)dr \tag{15}$$

where $r_{\max}$ and $r_{\min}$ represent the maximum radius and the minimum radius of the aerosol particle respectively. Therefore, the number of particles distributed in the cylinder is defined as follows.

$$X=\int_0^R\int_{r_{\min}}^{r_{\max}}n(r)\cdot\pi d^2drdz \tag{16}$$

The particle group backscattering signal, which is the integration of all one-particle backscattering signals, can be defined as follows:

$$P_{\Delta v}=\int_0^R\int_{r_{\min}}^{r_{\max}}P_{one}\cdot n(r)\cdot\pi d^2drdz \tag{17}$$

where P_{one} is the one-particle backscattering signal.

$$P_{one}=\frac{e^{-u(\lambda)z}\cdot\sigma_{bk}(\pi)}{z^2}P_{tr}(t) \tag{18}$$

where $\sigma_{bk}(\pi)$ is called the backscattering differential cross section that is based on the Mie theory. So the *SNR* of the echo signal (SNR_{bk}) affected by the particle group backscattering could be calculated as follows.

$$SNR_{bk} = \frac{P_{re}}{P_{bk}} \tag{19}$$

$$= \frac{P_{re}}{\int_0^R \int_{r_{\min}}^{r_{\max}} P_{one} \cdot n(r) \cdot \pi d^2 drdz} \tag{20}$$

$$= \frac{P_{tr} e^{-2u(\lambda)R} / z^2}{\int_0^R \int_{r_{\min}}^{r_{\max}} \frac{e^{-u(\lambda)z} \cdot \sigma_{bk}(\pi)}{z^2} P_{tr}(t) \cdot n(r) \cdot \pi d^2 drdz} \tag{21}$$

SNR_{bk} is calculated based on the target distance R and the fog visibility R_m in (21). Based on the simulation results using MATLAB, the relationship between SNR_{bk} and the target distance R is shown in Figs. 4 (a) and 4 (b). In Fig. 4 (a), SNR_{bk} of the echo signal is becoming poor when the target distance is increasing. In contrast, SNR_{bk} increases as the visibilities of fog get bigger.

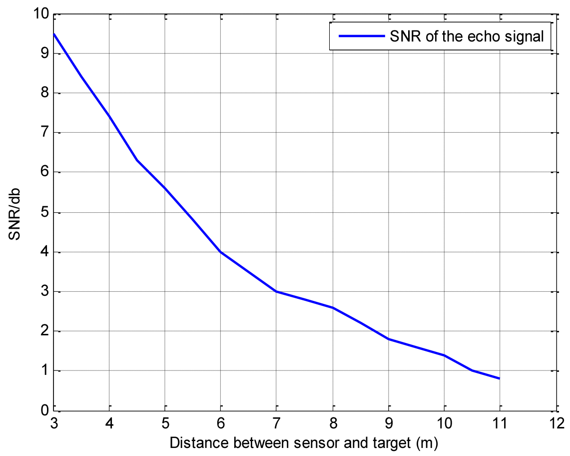


Fig. 4. (a) Simulation curve of SNR_{bk} as a function of target distance

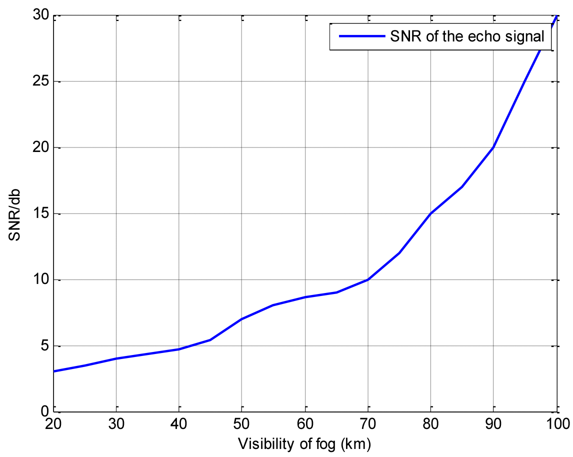


Fig. 4. (b) Simulation curve of SNR_{bk} as a function of visibility

IV. EXPERIMENTAL SETUP AND PROCEDURE

The block diagram of the experiment is shown in Fig. 5. The fog visibility can be adjusted via changing the fog density. It assumed that the atmospheric aerosol is relatively static in the chamber. The chirp signal from the direct digital synthesizer (DDS) board (AD9954, Analog Devices) is used to modulate a custom laser source with a power of 20mW. The laser wavelength is 635 nm. The output laser beam is split into two parts. One part is transmitted to a mixer as the local oscillator (LO) signal. The other part is transmitted to the target through a 12-m-long chamber. The echo signal is collected by an avalanche photodiode (APD, AD500-8). A wideband analog mixer (AD831) was used to mix the echo signal with the LO signal. The mixer output was then low-pass filtered to remove the high frequency noise and then digitized using an analog-to-digital convertor (ADC, AD7477) for further processing on PC. The experimental and simulation parameters are summarized as follows.

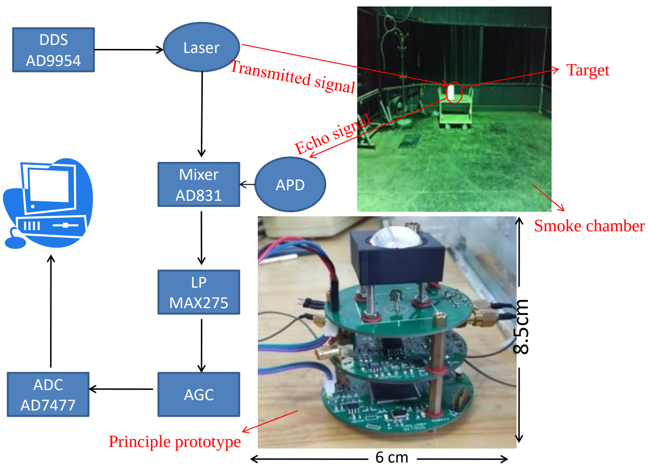


Fig. 5. The block diagram of the experiment for FMCW laser ranging system

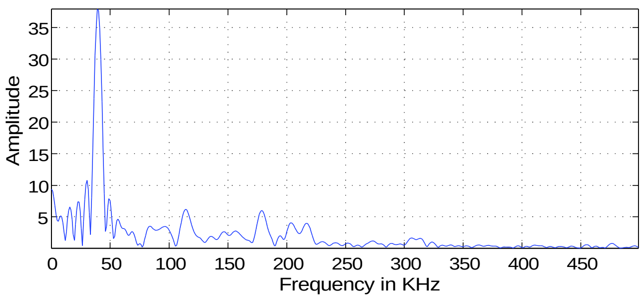
TABLE I
SUMMARY OF THE PARAMETERS USED IN THE EXPERIMENT

Parameter	Value	unit
System geometry		
Emitter-receiver separation	0.015	m
Receiver-target distance	5-12	m
Source parameters		
Wavelength	635	nm
Power	20	mw
Beam diameter	1.5	mm
Modulation frequency	10-110	MHz
Chirp duration	200	us
Receiver parameters		
Aperture	20	mm
APD active area	250	um
Focal length	18	mm
Optical system transmission	0.5	
Analog-digital converter bits	10	bit
Sample rate	600	KHz
Target characteristics		
Size(width)	0.2	m
Particle radius	1-30	um
Smog visibility	20-100	m

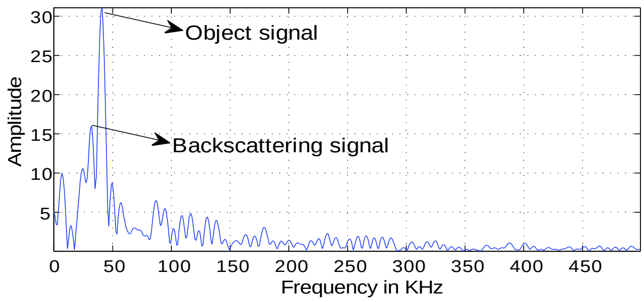
V. Analysis of Experimental Results

A. *Frequency spectrum analysis of echo signal*

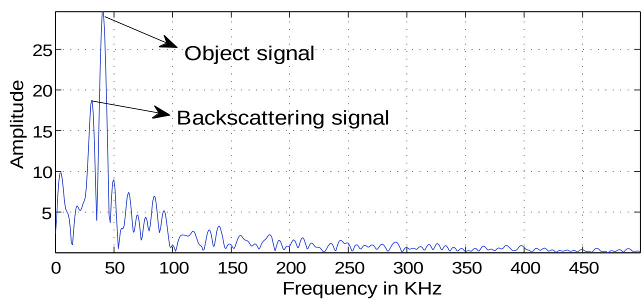
The experiment is performed in the chamber with different fog visibility. The frequency spectrum of the beat signal is presented in Fig. 6, and it shows that the amplitude of backscattering signal is increasing as the visibility reduces from 100m to 15m. Fig. 6 (c) clearly shows that the beat signal contains both the desired target signal and the backscattering signal that is consistent with (5). The frequency spectrum of the backscattering signal maintains approximately the same shape and position in Fig. 6 (a) to Fig. 6 (d) because of the homogeneous channel assumption and the same test environment. As shown in Figs. 6 (a), 6 (b) and 6 (c), the target echo signal can be easily detected in the presence of the backscattering signal. However, as the fog visibility dropped to 15m as shown in Fig. 6 (d), the target signal is not easy to be detected in the echo signal. From the above analysis, we can arrive at the conclusion that the FMCW laser ranging system has certain anti-interference ability in the fog when the visibility is not so bad.



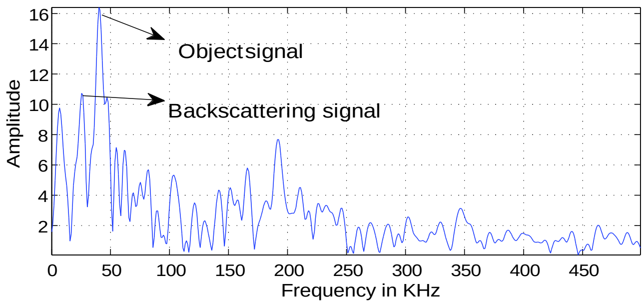
(a) The fog visibility is 100m.



(b) The fog visibility is 40m.



(c) The fog visibility is 20m.



(d) The fog visibility is 15m.

Fig. 6. The frequency spectrum of the beat signal with different visibilities

B. *Quantitative calculation model in FMCW laser ranging system*

In this part, the quantitative calculation model is validated using a real laser ranging system in the fog and the results are shown in Fig. 7 and Fig. 8. The SNR_{bk} obtained from the FMCW laser ranging experiment is calculated through frequency spectrum analysis, as shown in Fig. 6. Note that SNR_{bk} is the result of multiple averaging. In Fig. 7 (a), the SNR_{bk} based on both experimental results and simulation results decrease as the target distance increases. The maximum error and minimum error between the experimental and simulation results are 1.5dB and 0.8dB respectively when the fog visibility is 20m. In Fig. 7 (b), it has the similar conclusion. The maximum error and minimum error between experimental and simulation results are 1.8dB and 1.1dB respectively when the visibility is 40m. The error between the experimental results and simulation results is mainly because of the attenuation of the transmitted signal when the laser diode works for a long time. Additionally, the relationship between SNR_{bk} and fog visibilities based on (21) is shown in Fig. 8 (a) and Fig. 8 (b) when the target distance is 5 m and 10 m, respectively. The above analysis proves that the SNR_{bk} based on the quantitative calculation model is consistent with the real FMCW laser ranging experimental results.

The target distances obtained using the real FMCW laser ranging experiment in the fog with different visibilities are shown in Fig. 9 (a) and Fig. 9 (b). In Fig. 9 (a), when the nominal range is 6m, the detection error is 1m (17%) and the corresponding SNR_{bk} shown in Fig. 7 (a) is 1.8dB. The amplitude ratio of the target-reflected signal and the backscattering signal is 1.2 that makes the echo signal detection difficult. AS the target distance increasing, the ranging error is becoming greater and the ranging system will be completely ineffective as shown in Fig. 9 (a). It has the same situation when the visibility is 40m in Fig. 9 (b). Comparing the experimental results when the visibility is 20m and 40m, SNR_{bk} is greater when the visibility is 40m that is consistent with the curves in Fig. 4 (b). As the discussion above, the experimental and simulated results are in good agreement within acceptable error.

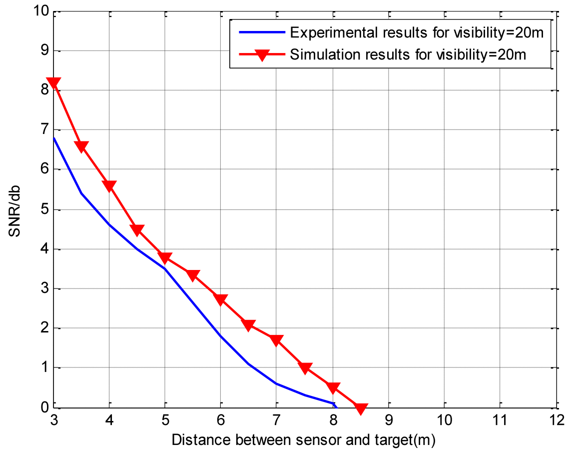


Fig. 7. (a) The curve of SNR_{bk} as a function of target distance when the visibility is 20m

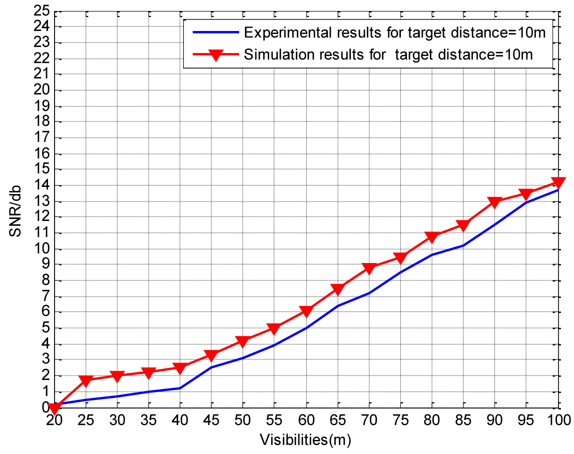


Fig. 8. (b) The curve of SNR_{bk} as a function of visibility when the target distance is 10m

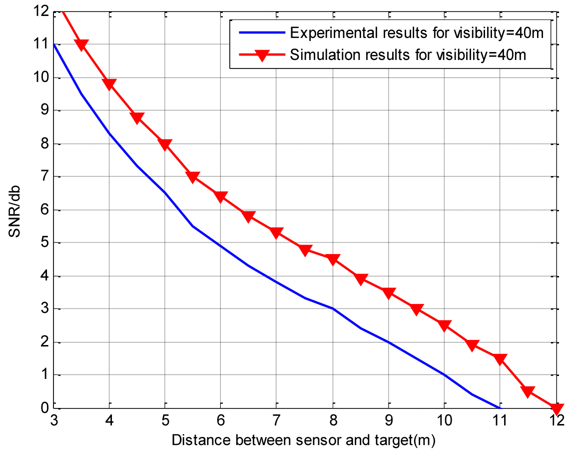


Fig. 7. (b) The curve of SNR_{bk} as a function of target distance when the visibility is 40m

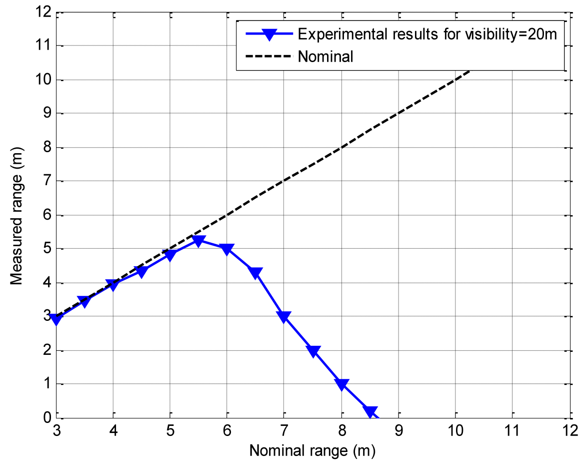


Fig. 9. (a) The ranging results when the visibility is 20m

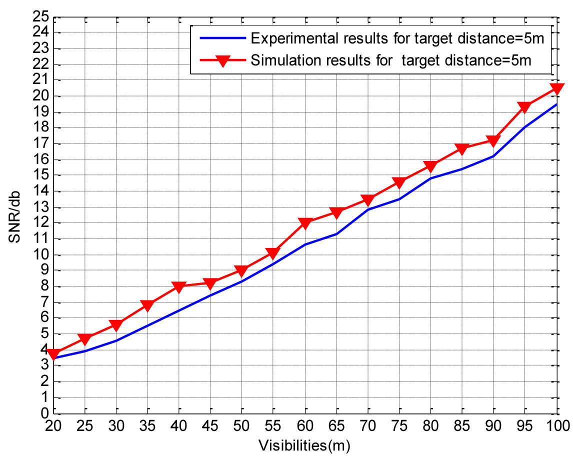


Fig. 8. (a) The curve of SNR_{bk} as a function of visibility when the target distance is 5m

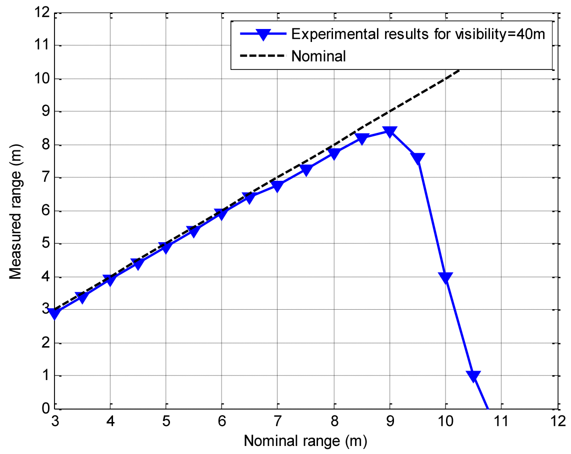


Fig. 9. (b) The ranging results when the visibility is 40m

VI. CONCLUSION

In this paper, we have proposed a quantitative calculation model based on Mie theory to analyze the signal-to-noise ratio (SNR) of the laser echo signal in backscattering environment. A FMCW laser ranging prototype that offers small size, low power and high resolution is designed and developed. Using both theoretical and experimental data from the FMCW laser ranging system, we demonstrated that the proposed quantitative calculation model is accurate and effective. In addition to what has been said, the quantitative calculation model proposed here is believed to provide novel insights in FMCW laser ranging technology in the fog, but it requires further study. Future work is focusing on two the main areas. The first is improving the quantitative calculation model where the aerosol particles movement should be taken into account. A second area is improving the ranging accuracy of the FMCW ranging technique. One possible variation would be to increase the bandwidth of a DDS signal, which can result in high ranging resolution.

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Yabo Duan was born in Henan, China, in 1989. He received his B.S in communication engineering from Henan Normal University, China, in 2011, and began the successive postgraduate and doctoral programs of study in Beijing Institute of Technology since 2011. He is now a PHD candidate in Intelligent detection and control engineering. His research interests include space target detection, non-linear signal processing, laser detection and identification.

Chengtian Song was born in Gansu, China, in 1977. He received the B. S degree from the Beijing Institute of Technology , Beijing, China, in 1999, the M.S degree from the Beijing Institute of Technology , Beijing, China, in 2002, all in Mechanical and Electronic Engineering, and the Ph. D. degree from the Beijing Institute of Technology, Beijing, China, in 2007, in Electrical and Electronics Engineering.

In 2002, he joined the Beijing Institute of Technology, where he is now an Associate Professor of Mechanical and Electronic Engineering, and has been the head of department since 2014. His current research interests include target detection theory, digital signal processing, weak signal detection, multiple detection methods and implementations.