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Phase noise reduction by using dual-frequency laser in coherent detection

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ABSTRACT

Dual-frequency laser radar (DFLR) uses laser with two coherent frequency components as transmitting wave. The method is based on the use of an optically-carried radio frequency (RF) signal, which is the frequency difference between the two components. Due to the two optical waves are generally subject to the same first order phase noise, the synthesis wave is predicted to have a stronger resistance to atmospheric turbulence than the single-frequency wave. To the best of our knowledge, the model proposed in this paper is the first model that detailedly illustrates that the dual-frequency laser has an advantage over the single frequency laser in atmospheric turbulence resistance. Experiments are carried out to compare the performances of single and dual frequency lidars under atmospheric turbulence. The experimental results show that, with the increase of atmospheric turbulence intensity, the signal to noise ratio (SNR) of beat signal decreases and its central frequency stability (CFS) becomes worse in conventional single frequency coherent laser radar (SFCLR). While for the DFLR, the SNR and CFS are almost unaffected by atmospheric turbulence, which are in good agreement with the theoretical model.

1. Introduction

Atmosphere is in constant motion, which forms gas vortexes with different temperature, pressure, densities and sizes. These vortexes are crosslinked and superimposed with each other to form a random turbulent motion [1]. When laser transmits in atmospheric turbulence, there will be random fluctuation in the wavefront of the transmitting beam, which may cause beam drift, expansion and scintillation, i.e., coherence degradation phenomenon [2]. All these effects can greatly deteriorate the laser's function in some applications. Thus the influence of turbulent atmosphere on laser beams is one of the most important issues to be considered in lidar [3,6].

Conventional SFCLR uses optical heterodyne detection which has the advantage of high sensitivity and the transmitted signal is a single-frequency laser beam [3]. Its reflection from the target is mixed at a photo detector with a reference "local oscillator" (LO) that is set at a close-by frequency. Ideally, the target's information (range and velocity) is obtained from the beat signal. Nevertheless, heterodyne detection is highly phase sensitive, the phase fluctuation caused by atmospheric turbulence will greatly broaden the spectral width of the beat signal and then decrease the SNR, lead to the central frequency jitter. Thus limiting the spectral resolution and lowering the accuracy of measurement [6]. Therefore, it is necessary to eliminate the influence of atmospheric turbulence on the signal and improve the detection performance as much as possible.

DFLR is a new concept of laser radar, which uses dual-frequency laser as transmitting wave to complete the measurement of hard target's range and speed, [4–8] and it can overcome those limitations in SFCLR. The frequency difference of the two optical components is in radio-frequency range [9]. The corresponding wavelength of the beat signal is in the range of centimeters to meters. Therefore, the impact of atmospheric turbulence on the phase of the beat signal is much weaker which improves the robustness to atmospheric turbulence [10,11]. The SNR and CFS of the beat signal are ensured and detection performance is improved.

Although the research of atmospheric turbulence influence on single-frequency laser transmission has been carried out extensively, [12,13] the influence of atmospheric turbulence on the beat signals in SFCLR and DFLR has never been studied systematically. Consequently, the aim of this paper is to investigate both theoretically and experimentally the effects of turbulent atmosphere on the SNR and CFS of the beat signal. In particular, we aim to show that DFLR has a higher capacity to resist atmospheric

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turbulence than SFCLR through comparison. The structure of this paper is as follows: Section 2 theoretically analyses the influences of atmospheric turbulence on the beat signal in both DFLR and SFCLR. The comparison of them is also conducted and simulation results are given. Section 3 we describe the experimental system used for this study and list the parameters of apparatus. In Section 4, the experimental results in both DFLR and SFCLR are presented. The SNRs and CFSs of the beat signal in different system are compared. Finally, the results, as well as the discussion of this work, are summarized in Section 5.

2. Theory

Suppose that we have a source filed $U_{1,2}(\vec{\rho}, k_{1,2})$, where $\vec{\rho}$ is the point's coordinates information in the transmitting plane, $k_{1,2}$ are the wave numbers. By employing the extended Huygens–Fresnel principle we can get the field $U(\vec{r}, z)$ in the receiving plane after experiencing atmospheric turbulence [14]:

$$U(\vec{r}, L, t) = U_1(\vec{r}, L, t)\exp[i(k_1L - \omega_1 t) + \theta_1(\vec{r}, \vec{\rho}, k_1)] + U_2(\vec{r}, L, t)\exp[i(k_2L - \omega_2 t) + \theta_2(\vec{r}, \vec{\rho}, k_2)] \quad (1)$$

where $\vec{r}$ is the point's coordinates information in the receiving plane; L stands for the transmitting distance; $\omega_{1,2}$ are the angle frequencies of the laser; $\theta_1(\vec{r}, \vec{\rho}, k_1)$ and $\theta_2(\vec{r}, \vec{\rho}, k_2)$ are the additional complex phases caused by turbulence during the spherical wave propagation [15].

The current $I(t)$ at the output of the detector is:

$$I(t) = G\Re \int_D \left|U(\vec{r}, L, t)\right|^2 d\vec{r} \quad (2)$$

where G is the gain of detector; $\Re$ is the responsivity of the photodetector; $\int_D$ denotes integration over the detector surface. Then the alternating current (AC) of the beat signal will be:

$$i_{beat}(t) = 2G\Re\cdot\mathrm{Re}\int_D U_1(\vec{r}, L, t)U_2^*(\vec{r}, L, t) \exp\left[\theta_1(\vec{r}, \vec{\rho}, k_1) + \theta_2(\vec{r}, \vec{\rho}, k_2)\right]\cdot\exp(i\Delta\omega t)d\vec{r} \quad (3)$$

where $\Delta\omega = \omega_1 - \omega_2$ is the angle frequency of the beat signal.

The general expression of the SNR is [8]:

$$SNR = \frac{<i_{beat}^2>}{<i_{shot}^2> + <i_{back}^2> + <i_{dark}^2> + <i_{th}^2>} \quad (4)$$

where $\langle\rangle$ denotes an ensemble average; $\left\langle i_{beat}^2\right\rangle$ is the mean square (MS) of the AC of the beat signal; $\left\langle i_{shot}^2\right\rangle$ is the MS of the signal shot noise current; $\left\langle i_{back}^2\right\rangle$ is the MS of the background shot noise current; $\left\langle i_{dark}^2\right\rangle$ is the MS of the dark current; $\left\langle i_{th}^2\right\rangle$ is the MS of the thermal noise current.

The $\left\langle i_{beat}^2\right\rangle$ is given by [14]:

$$<i_{beat}^2(t)> = 2G^2\Re^2\int_D\int_D <U_1^2(\vec{r}, L, t)> <U_2^2(\vec{r}, L, t)> \cdot < \exp\{2[\theta_1(\vec{r}, \vec{\rho}, k_1) + \theta_2(\vec{r}, \vec{\rho}, k_2)]\}> d^2\vec{r} \quad (5)$$

Because the difference of two laser wavelengths is very small, in isotropic medium, the effects of atmospheric turbulence on the respective single-frequency laser are approximately same and have a strong correlation. If it is assumed that the turbulence is statistically stationary and that the complex phase fluctuations induced by the turbulence are Gaussian random variables, it can be readily demonstrated that [15,16]

$$< \exp\left\{2\left[\theta_1(\vec{r}, \vec{\rho}, k_1) + \theta_2^*(\vec{r}, \vec{\rho}, k_2)\right]\right\} > = \exp\left[-\Gamma(\vec{r})\right] \quad (6)$$

Where

$$\Gamma(\vec{\vec{r}}) = < \left|\theta_1(\vec{r}, \vec{\rho}, k_1) - \theta_2(\vec{r}, \vec{\rho}, k_2)\right|^2 > \quad (7)$$

Here suppose the Gaussian distribution of the complex phase fluctuations has a mean value of a_n and a standard deviation of s_n.

$$a_n = k_{a,n}\cdot C_N^2 \quad (8)$$

$$s_n = k_{s,n}\cdot C_N^2 \quad (9)$$

where $k_{a,n}$ and $k_{s,n}$ are coefficients; C_N^2 is the atmospheric turbulence intensity.

For SFCLR system, the LO signal does not experience the atmospheric turbulence which means $\theta_2(\vec{r}, \vec{\rho}, k_2)$ is zero and the beat signal's complex phase fluctuation is entirely determined by $\theta_1(\vec{r}, \vec{\rho}, k_1)$. Because $\theta_1(\vec{r}, \vec{\rho}, k_1)$ obeys Gaussian distribution, based on the statistical relation $D(X) = E(X^2) - E^2(X)$ where $D(X)$ and $E(X)$ represents the standard deviation and mean value of variable X, respectively, we can get [17]

$$\Gamma_{SFCLR}(\vec{r}) = <\theta_1^2> = E_{SFCLR}(\theta_1^2) = D(\theta_1) + E^2(\theta_1) = a_1^2 + s_1^2 = (k_{a,1}^2 + k_{s,1}^2)\cdot(C_N^2)^2 \quad (10)$$

For DFLR system, both frequency components experience the atmospheric turbulence and their complex phase fluctuations can be approximately regarded the same. i.e. $a_1 \approx a_2$ and $s_1 \approx s_2$. Therefore, we can obtain

$$E(\theta_1 - \theta_2) = E(\theta_1) - E(\theta_2) \approx 0 \quad (11)$$

$$D(\theta_1 - \theta_2) = D(\theta_1) + D(\theta_2) - 2r\sqrt{D(\theta_1)}\cdot\sqrt{D(\theta_2)} \approx 2(1-r)s_1^2 \quad (12)$$

where r is the correlation coefficient of the variables θ_1 and θ_2, the statistical mean of beat signal's complex phase is

$$\Gamma_{DFLR}(\vec{r}) = <(\theta_1 - \theta_2)^2> = E_{DFLR}\left[(\theta_1 - \theta_2)^2\right] = D(\theta_1 - \theta_2) + \left[E(\theta_1 - \theta_2)\right]^2 = 2(1-r)k_{s,1}^2\cdot(C_N^2)^2 \quad (13)$$

The $\left\langle i_{shot}^2\right\rangle$ is given by:

$$\left\langle i_{shot}^2\right\rangle = 2e\Re GP_{in}B \quad (14)$$

where P_{in} is the total laser power on the detector surface. B is the electrical bandwidth.

The $\left\langle i_{back}^2\right\rangle$ is given by:

$$\left\langle i_{back}^2\right\rangle = 2e\Re GP_{back}B \quad (15)$$

where P_{back} is the total optical background power coupled onto the detector.

The $\left\langle i_{dark}^2\right\rangle$ is given by:

$$\left\langle i_{dark}^2\right\rangle = 2eI_{dark}B \quad (16)$$

where I_{dark} is the dark current.

The $\left\langle i_{th}^2\right\rangle$ is given by:

$$\left\langle i_{th}^2\right\rangle = \frac{4k_BTB}{R_L} \quad (17)$$

where k_B is the Boltzmann's constant; T is the system temperature and R_L is the load resistance of the detector.

Once inserted into Eq. (4), these different noise contributes to the SNR and the final expression of SNR is: