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A Correction Method of Lidar Measured Turbulence and its Validation by Using Metmast Data

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SUMMARY:
It is known that the turbulence intensity measured by using vertical doppler lidars has error. This paper aims to provide a correction method for lidar measured turbulence. It was found that the main cause of the error in the turbulence measurement by using vertical lidar is the vertical component of the turbulence. A correction method is proposed to reduce the effect of the vertical component and it is shown that the proposed method shows good agreement with the true turbulence. A correction factor is proposed to consider the effect of the range gate length in lidar measurement. After applying the proposed correction factor and coefficient, the measured 90 percentile of the turbulence intensity by using vertical lidar shows good agreement with that measured by sonic anemometer.

Keywords: vertical doppler lidar, turbulence measurement, floating lidar,

1. INTRODUCTION

Fixed and floating vertical Doppler lidars have been used for the assessment of mean wind speed. However, the measurement of the turbulence, which is needed for the assessment of the turbine fatigue loading, has some errors compared to the conventional cup or sonic anemometers (Mann et al., 2017) and the cause of this error is not clarified. The floater motion causes additional uncertainty in the turbulence measurement of the floating lidar as reported by Yamaguchi and Ishihara (2016). For fixed lidars, a method by Thiébaut et al. (2022) was proposed to measure the turbulence by using the variance of Line of Sight (LoS) wind speed, but this method is not applicable to floating lidars because of the change of the LoS direction caused by the floater motion. Tanemoto et al. (2023) proposed a method to correct errors due to the range gate length in turbulence measurement by Scanning Doppler lidars. However, the applicability of this method to the vertical lidar is not yet made clear.

In this study, first the cause of the error of turbulence measurement by using the vertical lidar is clarified. A correction method for the lidar measured turbulence is then proposed. Finally, the effect of range gate length is corrected to measure horizontal turbulence by using vertical lidar.

2. METHODOLOGY

2.1. Analysis of the cause of the error of the lidar measured turbulence

In this study, a vertical Doppler lidar, Windcube v2 is used. The Line of Sight (LoS) velocity is measured at time i in the direction of North (V_1), East (V_2), South (V_3), West (V_4) and vertically upward (V_5) as shown in Figure 1. When the wind field is assumed to be steady during the measurement period, the east-west component of the horizontal wind speed u_{Lidar} can be calculated by using Equation (1).

$$u_{\mathrm{Lidar}} = \frac{V_2 - V_4}{2\sin\theta_0} \tag{1}$$

Let $u_j = \overline{u_j} + u'_j$ and $w_j = w'_j$, and assume that the wind field is horizontally homogeneous ($\overline{u_2} = \overline{u_4} = \bar{u}$), then the horizontal velocity measured by lidar u_{Lidar} can be written by using Equation (2).

$$u_{\mathrm{Lidar}} = \bar{u} + \frac{1}{2}(u'_2 + u'_4) + \frac{\cos\theta_0}{\sin\theta_0}(w'_2 - w'_4) \tag{2}$$

Thus, the variance of the lidar measured horizontal velocity can be calculated as follows.

$$\sigma_{\mathrm{Lidar}}^2 = \frac{1}{2}\sigma_u^2 + \frac{1}{2}\rho_{uu}\sigma_u^2 + \frac{\cos^2\theta_0}{2\sin^2\theta_0}\sigma_w^2(1-\rho_{ww}) + \frac{\cos\theta_0}{2\sin\theta_0}\left(\overline{u'_2 w'_2} - \overline{u'_2 w'_4} + \overline{u'_4 w'_2} - \overline{u'_4 w'_4}\right) \tag{3}$$

where the standard deviations of velocity components are assumed to be horizontally uniform and the correlations of the fluctuating wind speed between two measurement locations are defined as $\rho_{uu} = \overline{u'_2 u'_4}/\sigma_u^2$ and $\rho_{ww} = \overline{w'_2 w'_4}/\sigma_w^2$. The magnitude of the each term in Equation (3) is evaluated by using synthetic turbulent wind field which has the specified power spectrum and cross spectrum.

2.2. Correction of measured turbulence by using vertical lidar

According to Thievaut et al. (2022), the standard deviation of the horizontal wind speed can be calculated by using the standard deviation of LoS wind speed as follows. The variances of LoS wind speed ${\sigma_{V2}}^2$ and ${\sigma_{V4}}^2$ can be calculated as follows from Equation (4) .

$$\begin{gathered} {\sigma_{V2}}^2 = \sigma_{u_2}^2 \sin^2\theta_0 + \sigma_{w_2}^2 \cos^2\theta_0 + 2\overline{u'_2 w'_2}\sin\theta_0\cos\theta_0 \\ {\sigma_{V4}}^2 = \sigma_{u_4}^2 \sin^2\theta_0 + \sigma_{w_4}^2 \cos^2\theta_0 - 2\overline{u'_4 w'_4}\sin\theta_0\cos\theta_0 \end{gathered} \tag{4}$$

If the wind field is assumed to be steady and homogeneous, ($\sigma_{u_2}^2 = \sigma_{u_4}^2 = \sigma_u^2,\ \sigma_{w_2}^2 = \sigma_{w_4}^2 = \sigma_w^2,\ \overline{u'_2 w'_2} = \overline{u'_4 w'_4}$), the standard deviation of the horizontal wind speed can be obtained as follows.

$$\sigma_u^2 = \frac{1}{2\sin^2\theta_0}\left({\sigma_{V2}}^2 + {\sigma_{V4}}^2 - 2\sigma_w^2\cos^2\theta_0\right) \tag{5}$$

As mentioned in Section 2.1, the differences between the standard deviation of the true horizontal wind speed and lidar measured horizontal wind speed is a function of the ratio of the vertical turbulence to the horizontal turbulence, i.e., σ_w/σ_u. In this study a correction factor of the lidar maeasured horizontal turbulence is proposed by using the ratio of the standard deviation of the lidar measured horizontal wind speed (Equation (3)) and true turbulence intensity (Equation (5)) by using the synthetic wind field as shown in Equation (6).

$$\psi(\sigma_w/\sigma_u) = \sqrt{\frac{\sigma_u^2}{\sigma_{\mathrm{Lidar}}^2}} \tag{6}$$

2.3 Correction of range gate length

The effect of the range gate length has to be considered when the proposed method is applied to the measurement data. In case of WindCube V2, the range gate length is set to 20m, i.e., when wind speed at 80m above ground level, the averaged wind speed between 70m and 90m above ground level is measured. This results in the underestimation of the measured turbulence. In this study, the method proposed by Tanemoto et al. (2022) is used to consider this effect. By using the synthetic wind field, following correction term is calculated as function of mean wind speed.

$$\phi(u) = \sigma_{\mathrm{u}}(u) - \sigma_{\mathrm{ave}}(u) \tag{7}$$

Here, $\sigma_{\mathrm{ave}}(u)$ is the standard deviation of horizontal wind speed averaged over the height between 70m and 90m, and $\sigma_{\mathrm{u}}(u)$ is the standard deviation of the horizontal wind speed at 80m. Both of terms are the function of the mean wind speed. Finally, the standard deviation of the horizontal wind speed is calculated by using the standard deviation of the lidar measured horizontal wind speed, the correction factor in Equation (6) and the correction term in Equation (7) as shown in Equation (8). The proposed method is applied to the lidar measurement at Choshi offshore site and compared with the sonic anemometer measurement at 80m above sea level.

$$\sigma_{\mathrm{u}}(u) = \psi(\sigma_w/\sigma_u)\sigma_{\mathrm{lidar}} + \phi(\mathrm{u}) \tag{8}$$

3. Results

Figure 2 shows each component of the variance of the lidar measured horizontal velocity in Equation (3). It is clear that when the fluctuating component of vertical wind speed is larger, the lidar measured horizontal turbulence is overestimated. On the other hand, when the vertical turbulence is smaller, the lidar measured turbulence is underestimated. The first two terms in Equation (3) are not related to vertical turbulence and shows constant value. The third term is proportional to the vertical turbulence and causes the overestimation of the lidar measured turbulence.

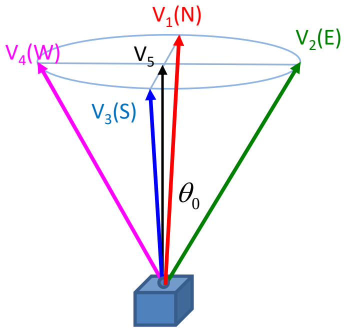

Figure 1 Vertical lidar measurement

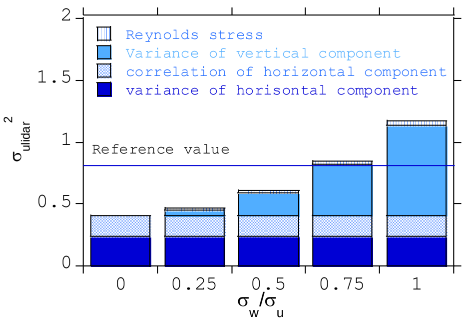

Figure 2 The cause of the variance of the lidar measured fluctuating horizontal velocity as shown in Equation (3)

Figure 3 shows the proposed correction factor in Equation (6) and Figure 4 illustrates the normalized standard deviation of the lidar measured horizontal wind speed before and after correction by using the correction factor. After applying the correction, the overestimation of the standard deviation of the horizontal wind speed is improved.

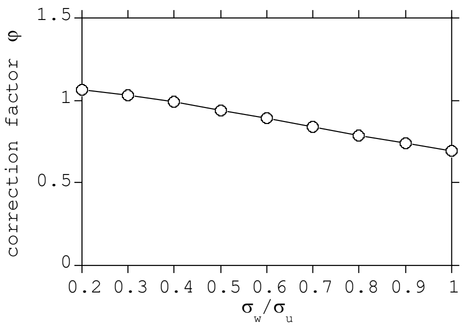

Figure 3 Proposed correction factor $\psi(\sigma_w/\sigma_u)$

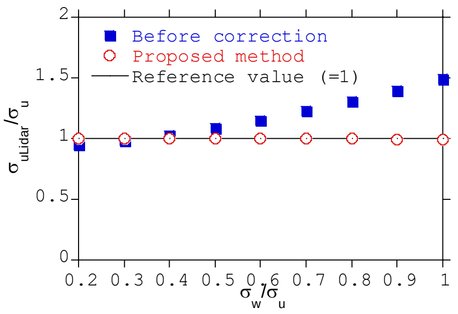

Figure 4 Standard deviation of lidar measured horizontal wind speed before and after correction

Figure 5 plots the proposed correction term in Equation (7) and Figure 6 shows the 90 percentile of turbulence intensity before and after applying the proposed correction in comparison with the measurement by the sonic anemometer. After applying the proposed correction, the lidar measured turbulence intensity shows good agreement with the sonic anemometer measurement.

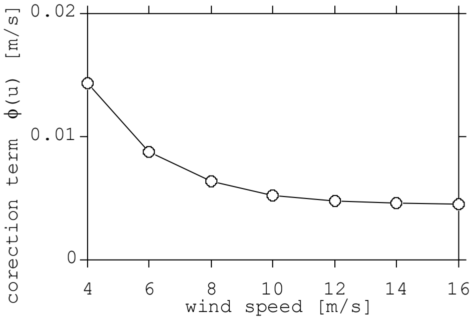

Figure 5 Proposed correction term $\phi(u)$

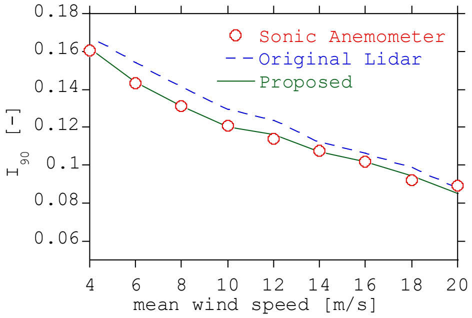

Figure 6 90 percentile of turbulence intensity (I_{90})

4. CONCLUSITONS

It was found that the main cause of the error in the turbulence measurement by using vertical lidar is the vertical component of the turbulence. A correction method is proposed to reduce the effect of the vertical component and it is shown that the proposed method shows good agreement with the true turbulence. A correction term is proposed to consider the effect of the range gate length in lidar measurement. After applying the proposed correction factor and correction term, the measured 90 percentile of the turbulence intensity by using the vertical lidar shows good agreement with that measured by sonic anemometer.

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